L-Band RF System & Main Linac Integration Programs

June 9-10, 2010 ART Review

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General Goals:

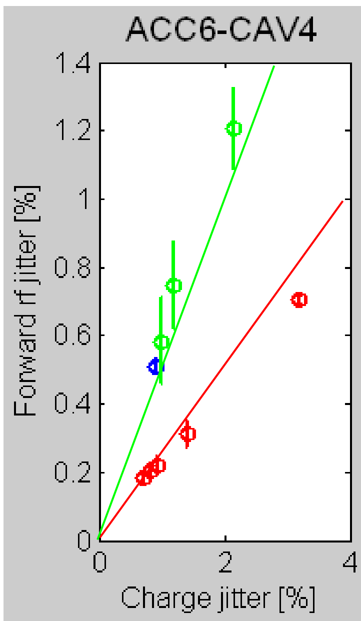
- Develop more reliable and lower cost L-band RF source components for the ILC linacs.
- Verify performance goals of the rf system
- Address linac issues that span subsystem boundaries

Main Linac Integration

- Study pulse-to-pulse gradient stability in the FLASH cavities at DESY to evaluate rf overhead and model gradient control
- Evaluate the effectiveness of the cryomodule 70 K HOM absorbers in preventing a significant fraction of the beam induced, high frequency (above cavity cutoff) wakefield energy from being dissipated in the 2 K accelerator
- Study effect of the coarser beam energy control associated with the Klystron Cluster rf distribution scheme on the linac beam emittance – just starting.

FLASH Input RF and Gradient Stability with Beam and Feedback On

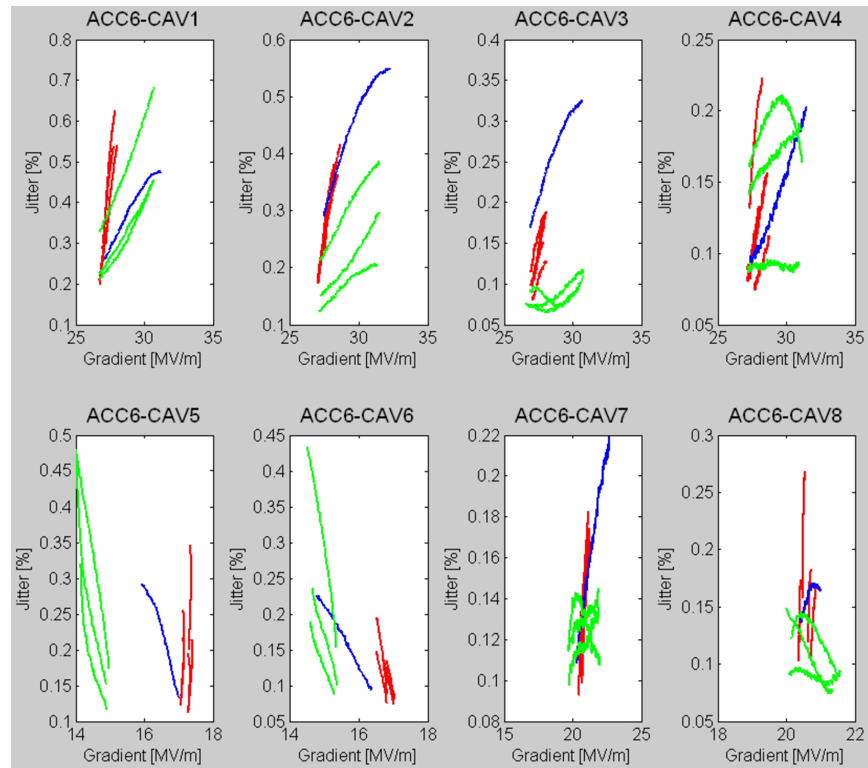
Input RF Jitter



Red: 3 mA beam with piezos off;
Expect slope of ¼ (red line)

Blue: 9 mA beam with piezos off;
Green: 9 mA beam with piezos on.
Expect slope of ½ (green line)

Cavity Gradient Jitter



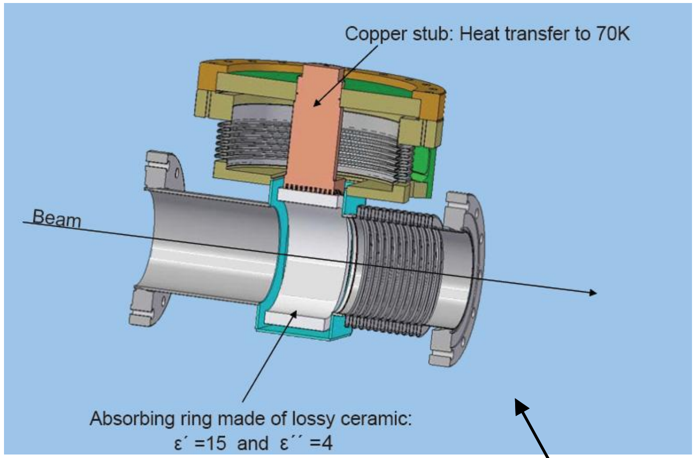
Red: 3 mA beam with piezos off
Blue: 9 mA beam with piezos off
Green: 9 mA beam with piezos on

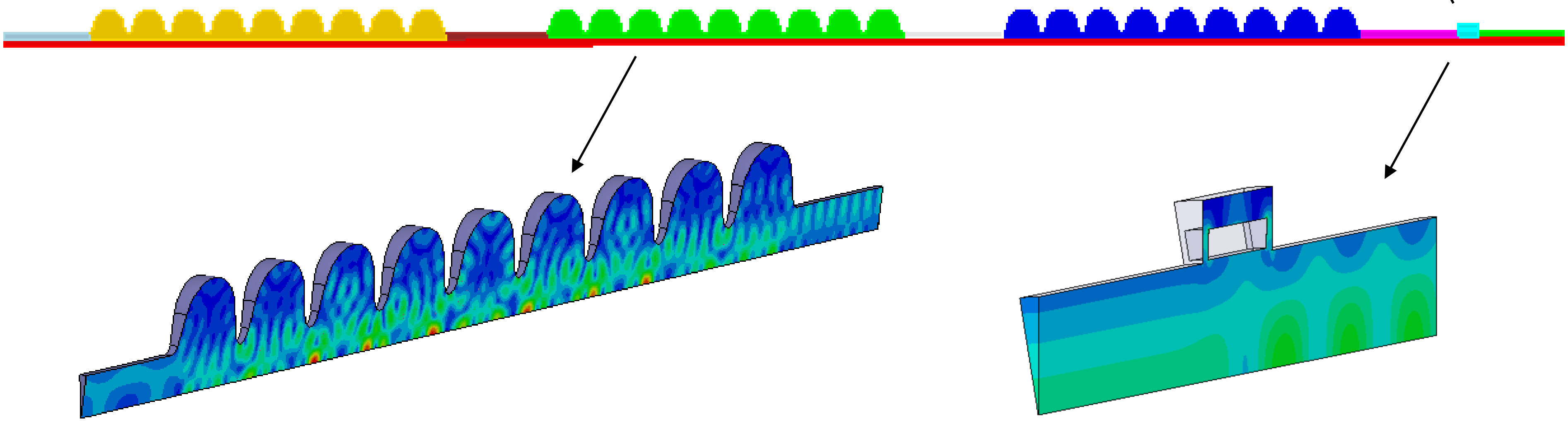
Effectiveness of Beamline HOM Absorbers

Goal: verify that beam pipe losses at 2K are small compared to losses in 70 K absorbers

Compute S-Matrixes for 4-20 GHz TM0n mode propagation through cavities and absorber

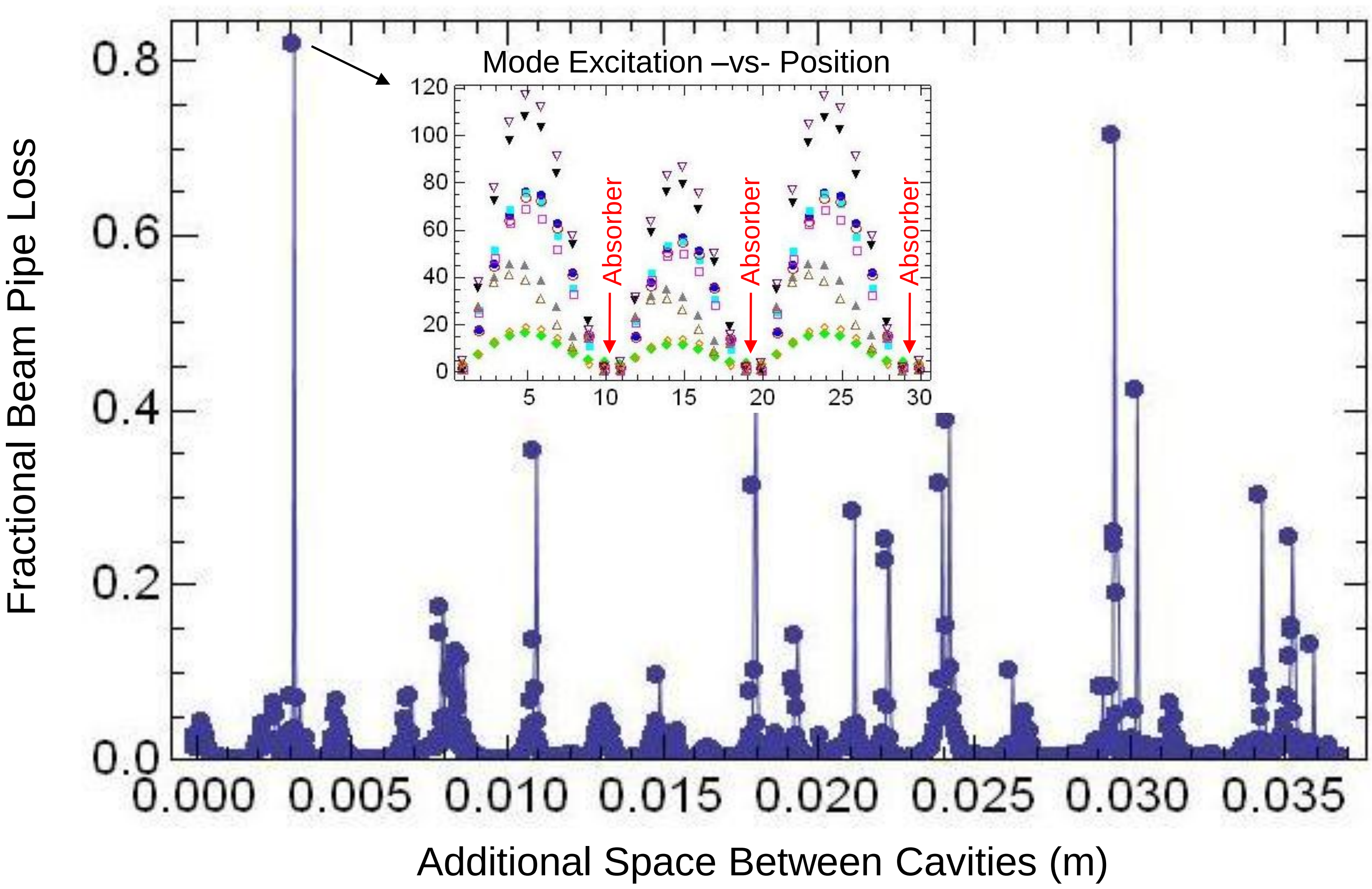
Cascade results to compute power loss profile in 8 cavity + 1 absorber strings





Fractional Beam Pipe Loss Vs Cavity Spacing

20 GHz: 5 TM0n Modes



Statistics on Fractional Pipe Losses

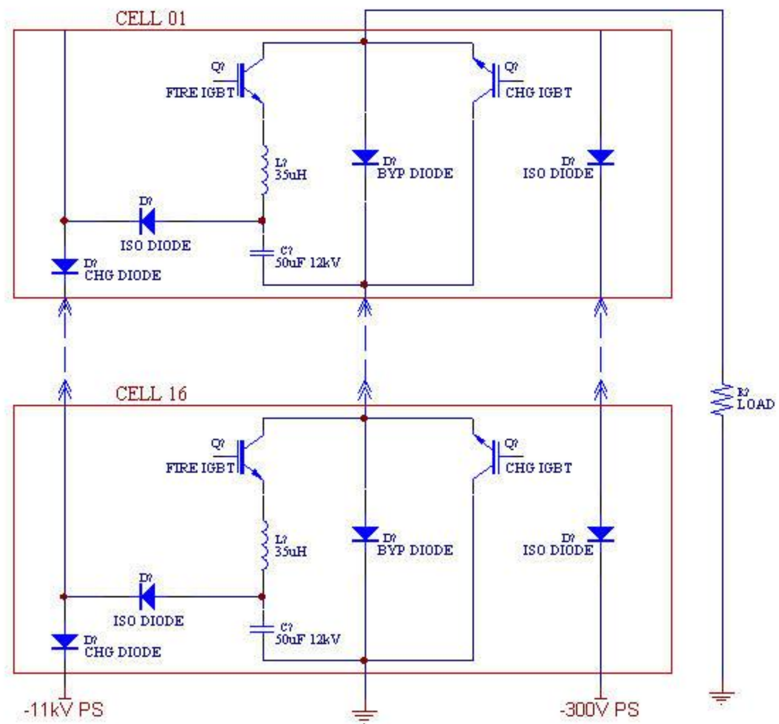
f [GHz]	Average	RMS	.90 quantile
4	.081	.086	.108
8	.012	.005	.018
12	.046	.111	.079
16	.084	.144	.216
20	.078	.138	.146

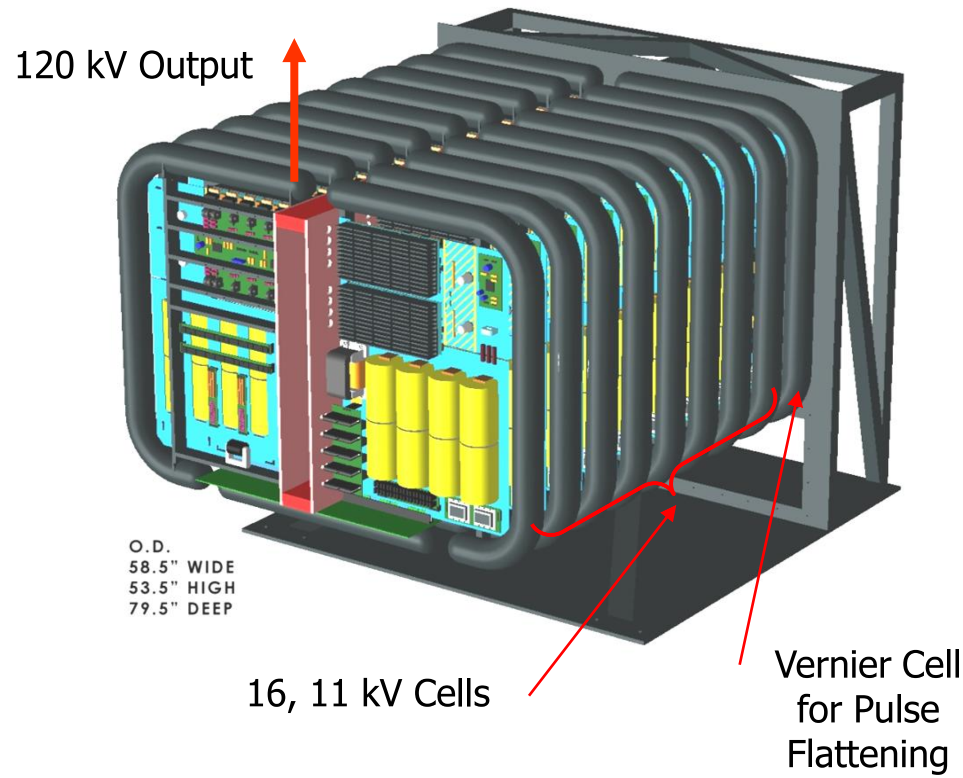
Marx Modulator

- **Goals:**
  - Develop Marx Modulator approach as an alternative to the ILC baseline Pulse Transformer Modulator with Bouncer
    - Reduces cost, size and weight, improves efficiency and eliminates oil-filled transformers
- **Project Status:**
  - First SLAC Prototype (P1) has run ~1500 hours powering a 10 MW Toshiba Multi-Beam Klystron (MBK) without fundamental problems.
  - Building upon the experience with the P1 Marx, the SLAC P2 Marx is currently in the final stages of design. There is no arraying of solid-state switches within a cell, simplifying the control and protection schemes, and the layout is redesigned to have single-side access.

SLAC P1 Marx Modulator

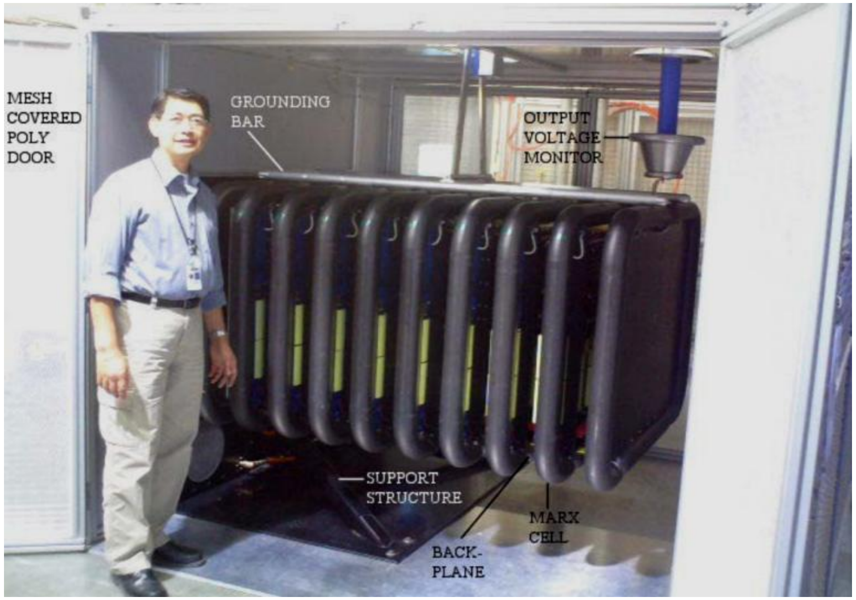
(120 kV, 140 A, 1.6 ms, 5Hz)

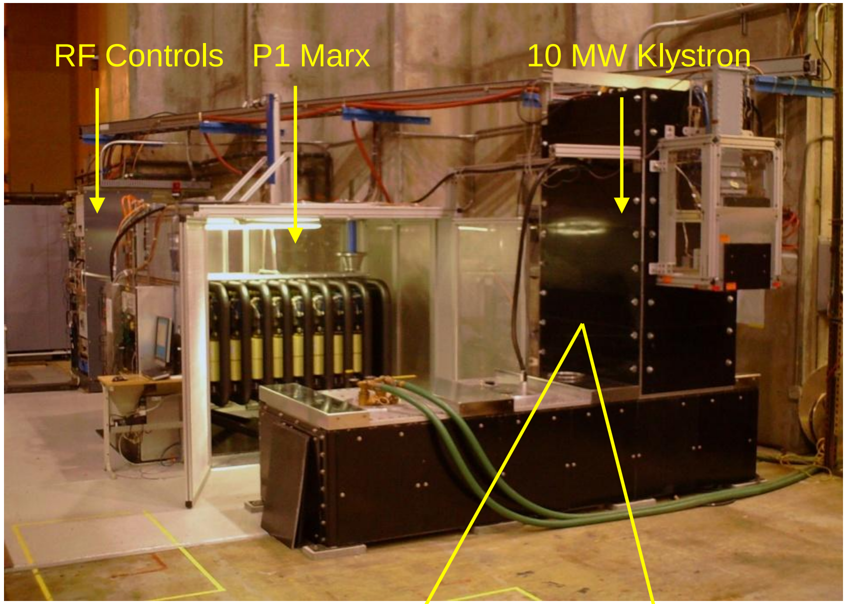




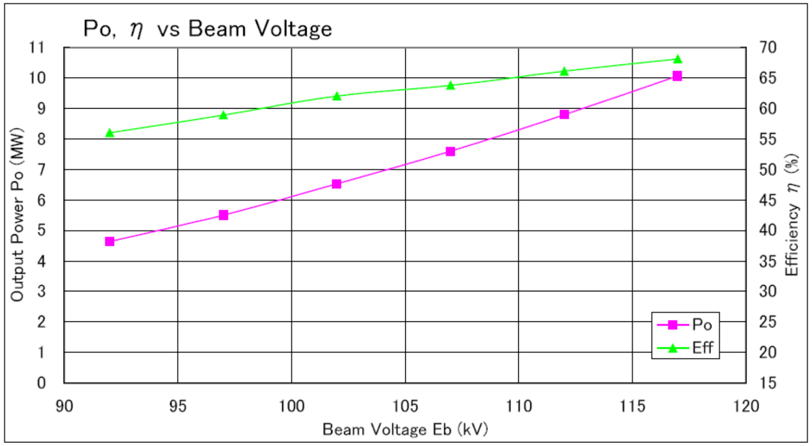
- 11 kV per cell (11 turn on initially, 5 delayed for coarse droop compensation)
- Switching devices per cell: two 3x5 IGBT arrays
- Vernier Cell (‘Mini-Marx’) flattens pulse to 1 kV

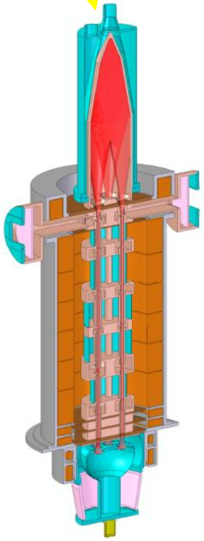
P1 Marx Test Stand at SLAC ESB



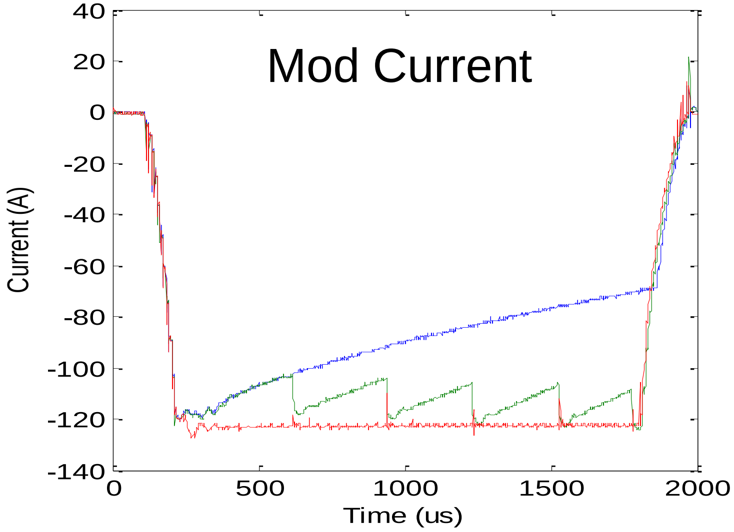


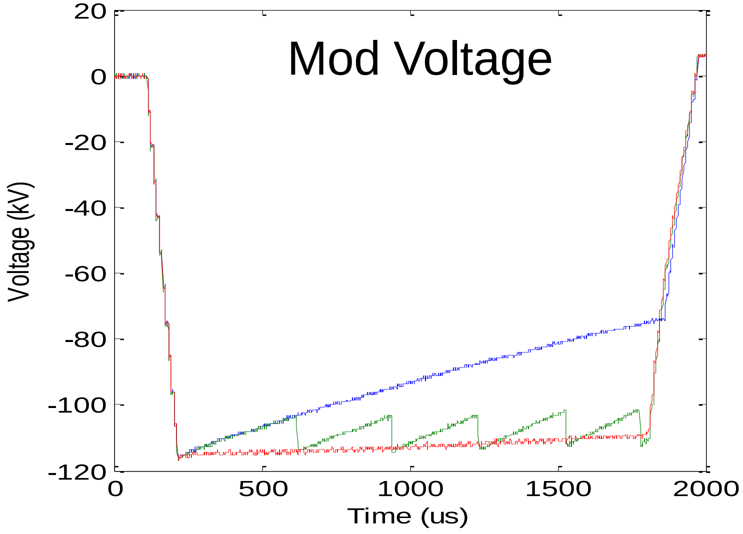
Toshiba MBK Measurements of Efficiency and Output Power -vs- Beam Voltage

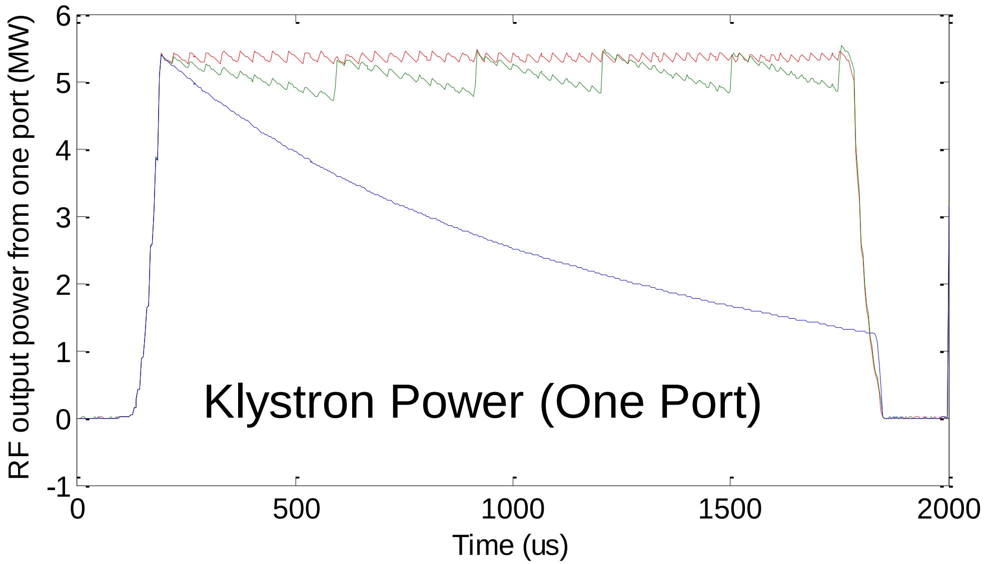




Marx and MBK Output with Different Levels of Droop Compensation





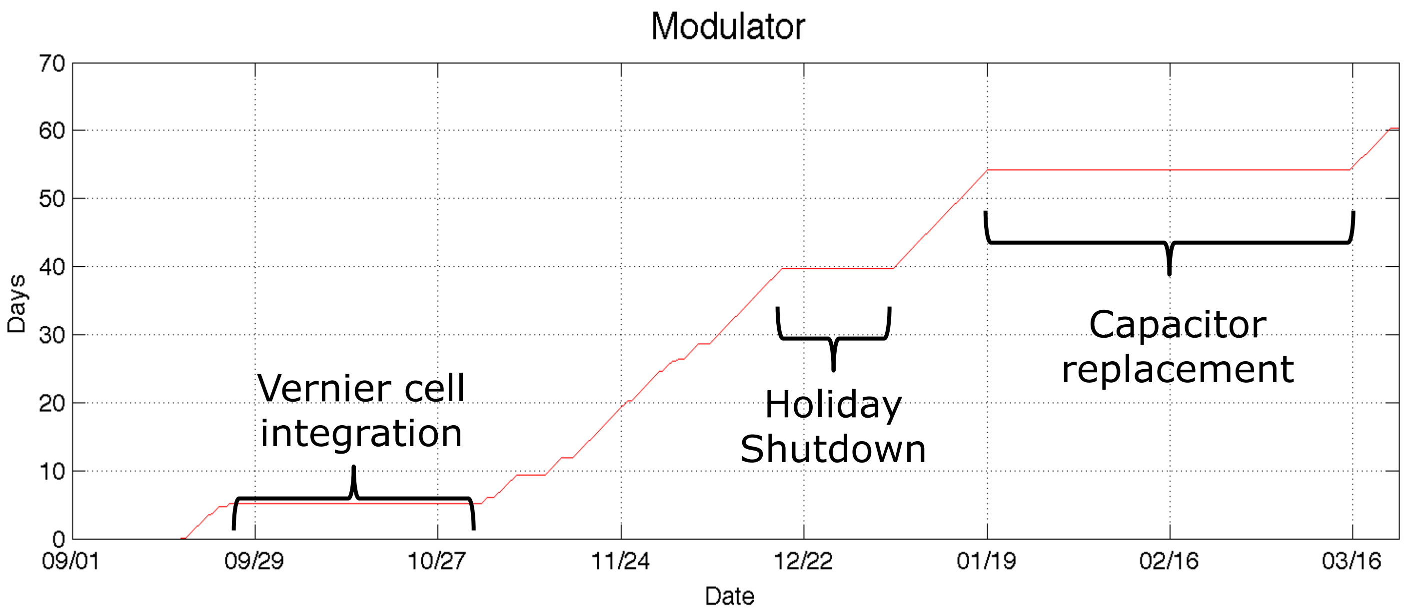


Blue: no droop compensation

Green: with only delay cells

Red: with delay cells and Vernier – flat with 3% saw-tooth modulation

P1 Operational History



1450 hours (60 days) integrated operation with klystron [additional ~ 400 hours with test load]

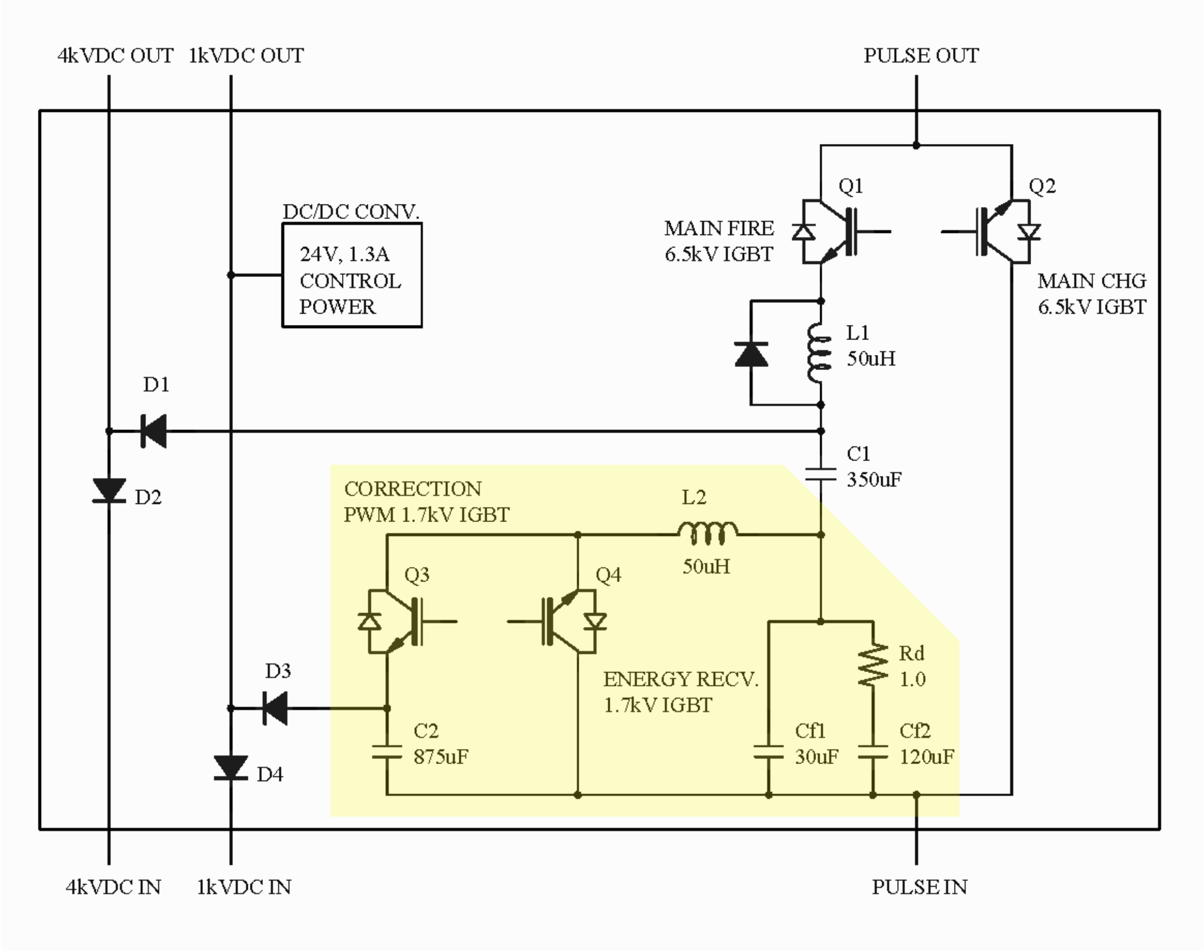
Maintenance downtime: replace energy storage capacitors damaged by improper voltage grading

Design Evolution to the P2-Marx

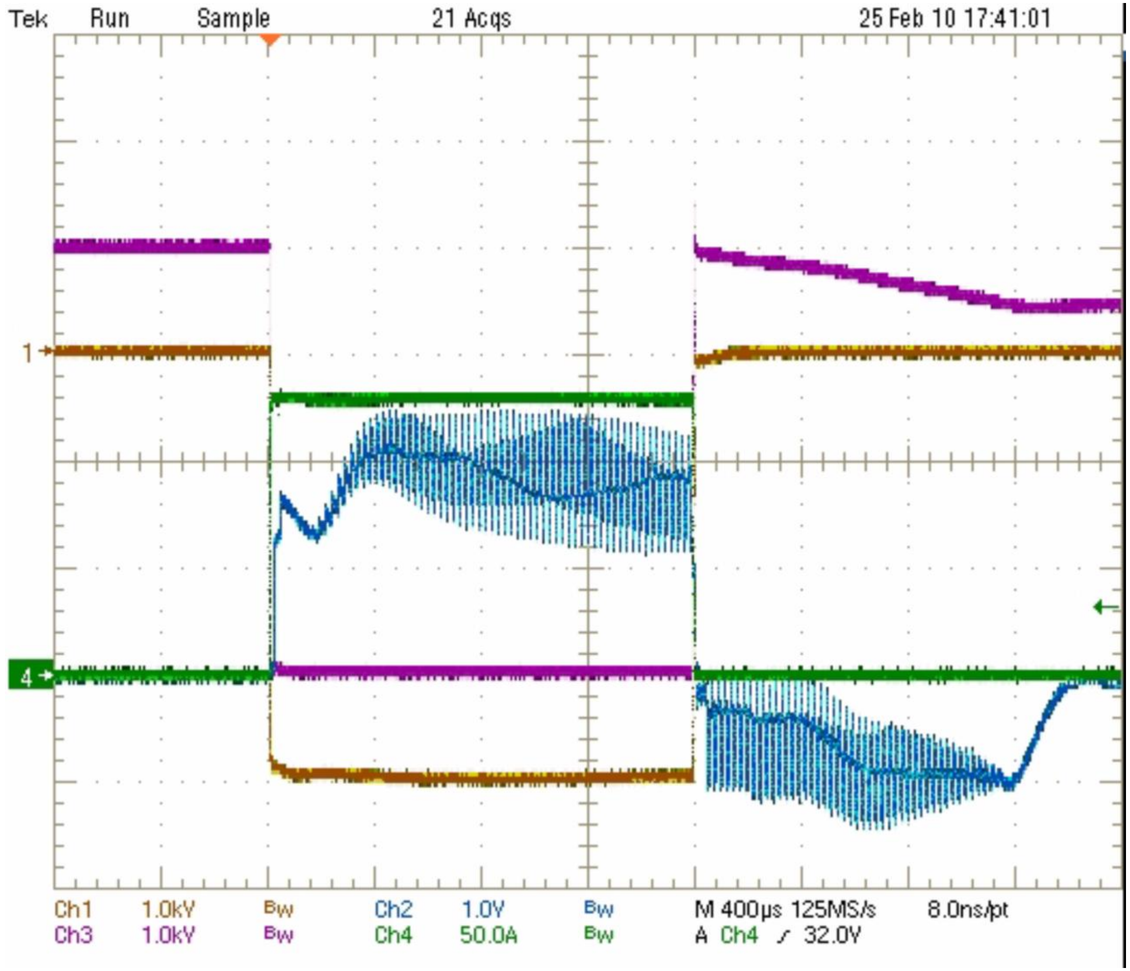
- 2nd Generation design builds on P1 experience
- Improved HA architecture
  - Truly modular topology; single repeated cell design
  - Droop compensation (via PWM) integrated into each cell
  - 4 kV cell voltage eliminates series switch arrays
  - Enhanced control system with increased diagnostics
- Engineering refinements
  - Reliability evaluation: 10^5 hour life
    - Voltage margin on silicon
    - Capacitor energy density
  - Decreased overall size by ~20%
- Prototype cell undergoing testing
- Expected completion in FY11

P2 Cell: Simplified Schematic

- Basic cell circuit similar to P1
- Includes Correction circuit (shaded) where pulse width modulation (Q3) compensates droop as C1 discharges: C1+Cf1 voltage stays constant



P2 Cell Output Voltage Regulation

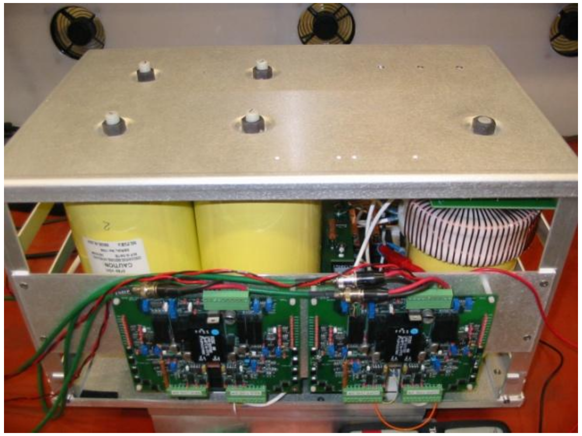


Cell Output Current

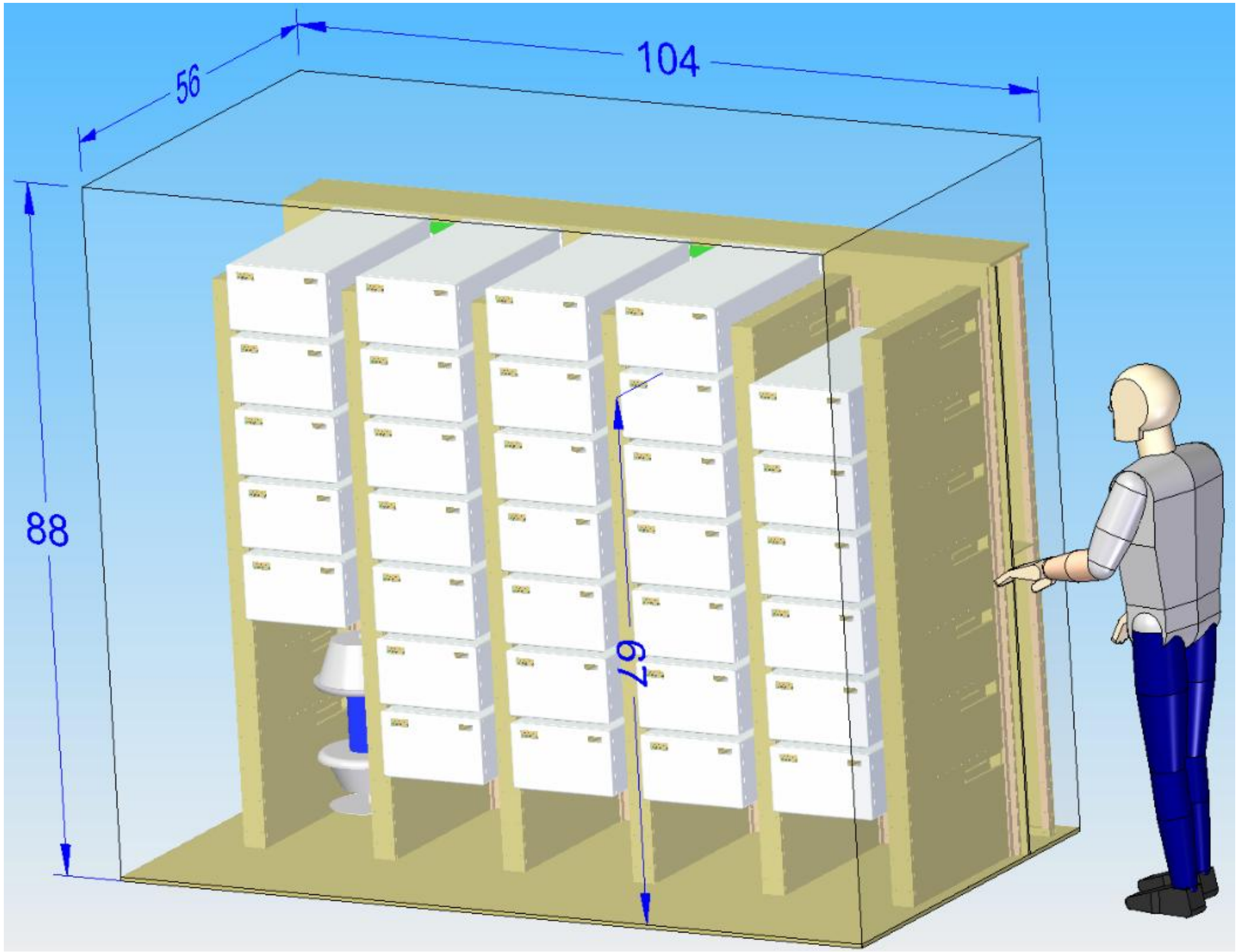
Cell Output Voltage

Main IGBT V_{ce}

PWM Inductor Current



Conceptual Design of P2-Marx



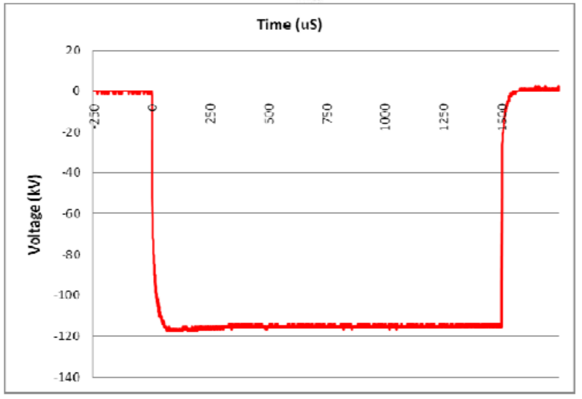
Diversified Technologies Inc. (DTI) Marx Modulator

This Marx was SBIR funded and will be delivered to SLAC after it is modified to improve ease of use. It has 6 kV cells that are immersed in oil, electrolytic capacitors (half the droop) and 900 V vernier cells.

Full Unit

Inside Layout

Marx Cell



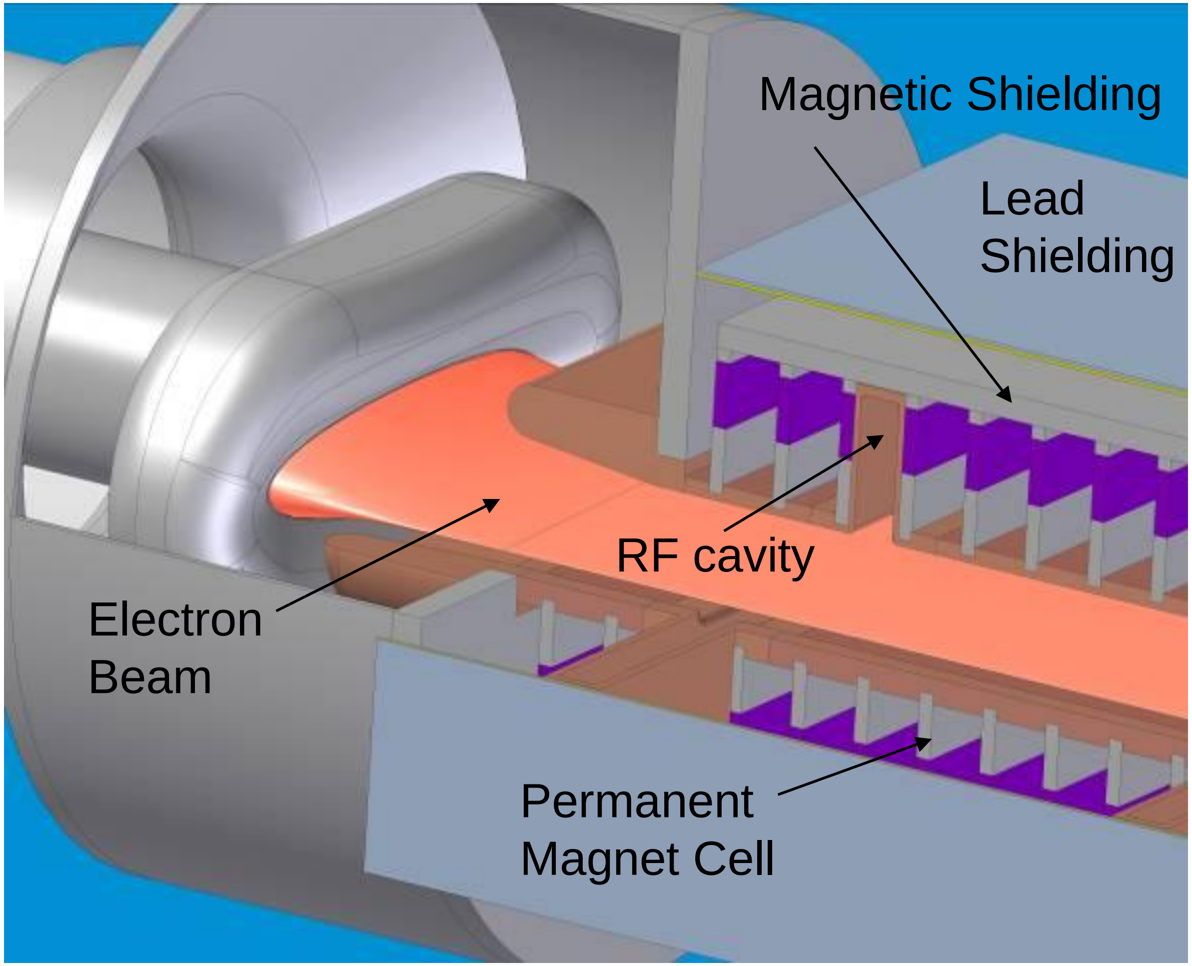
Measured Voltage Waveform

Sheet Beam Klystron Development

- **Goals:**
  - The Sheet Beam Klystron (SBK) originally envisioned has a 40:1 beam aspect ratio and utilizes permanent magnet focusing, making it smaller, lighter and less expensive than the baseline MBK
  - SBK would be plug-compatible and have similar efficiency as the MBK
  - Both a Beam Tester and full SBK were to be built so the issues of beam generation, transport and rf operation can be studied separately
- **Project Status:**
  - Beam Tester complete and has run at full peak power with ~1 us pulses, producing an elliptical beam
  - In simulations, discovered strong beam-induced transverse modes that drive beam into drift tube wall. No easy fixes except to use ~ 1kG solenoidal focusing
  - With the long development time still required and smaller costs savings with solenoidal focusing, will end program in FY10 after a two-cavity, permanent-magnet focused section is operated to qualify the MAGIC 3D PIC code.

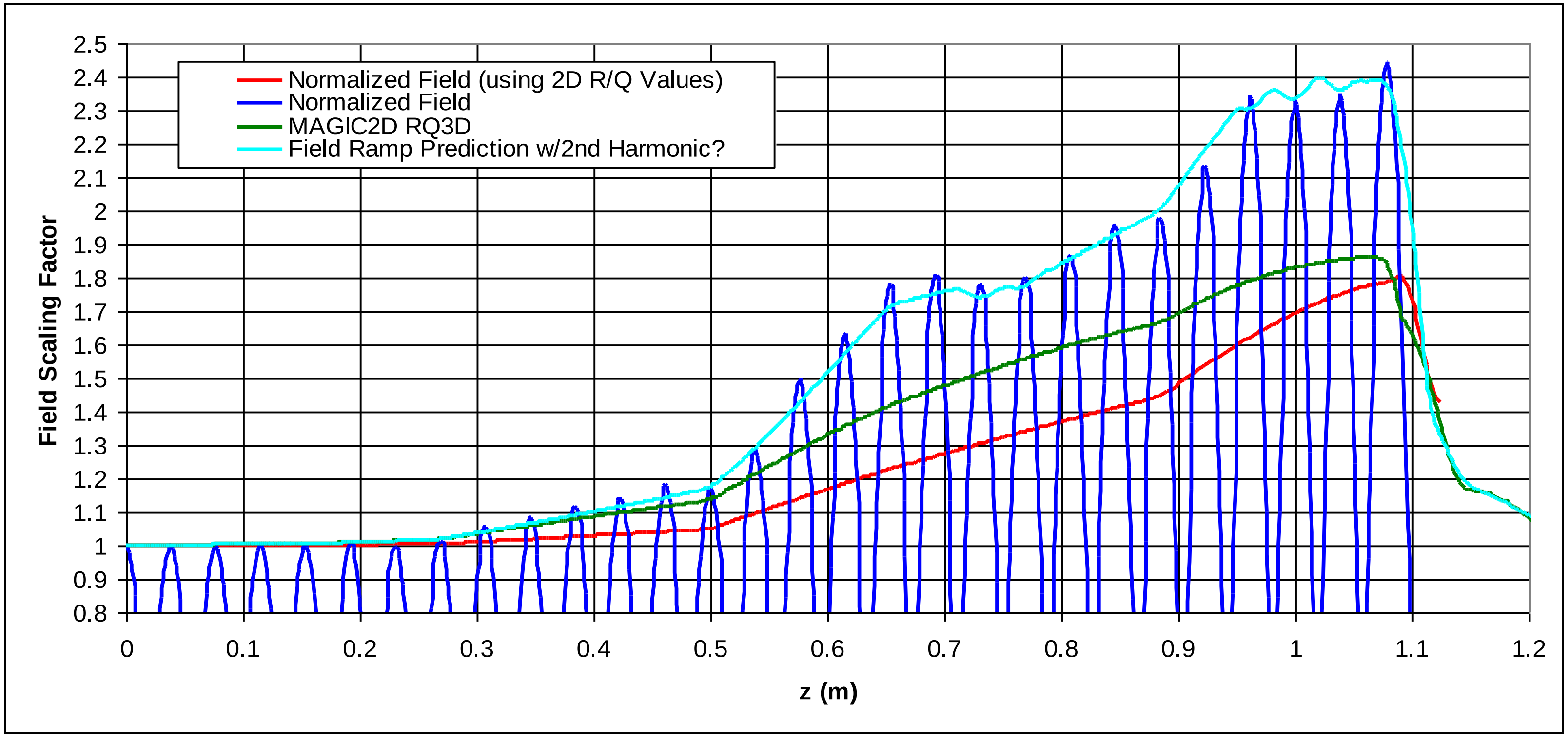
Beam Transport and RF

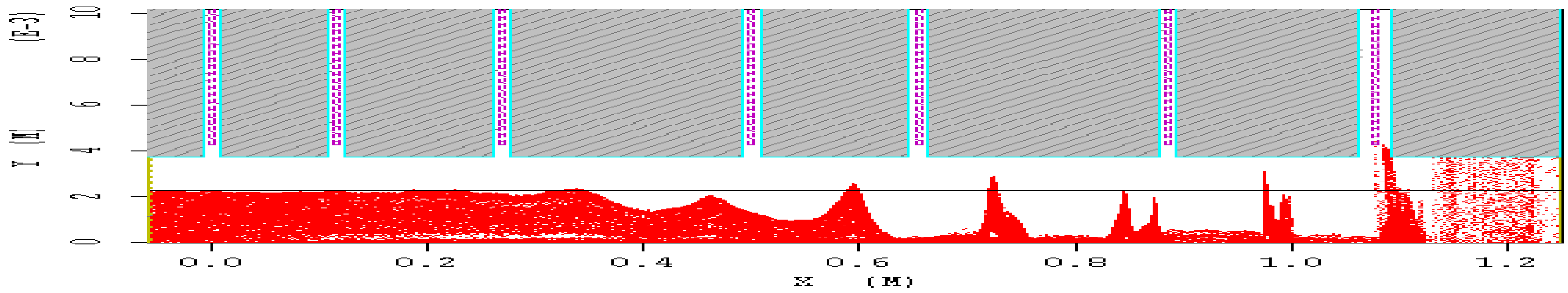
An elliptical beam is focused in a periodic permanent magnet stack that is interspersed with rf cavities



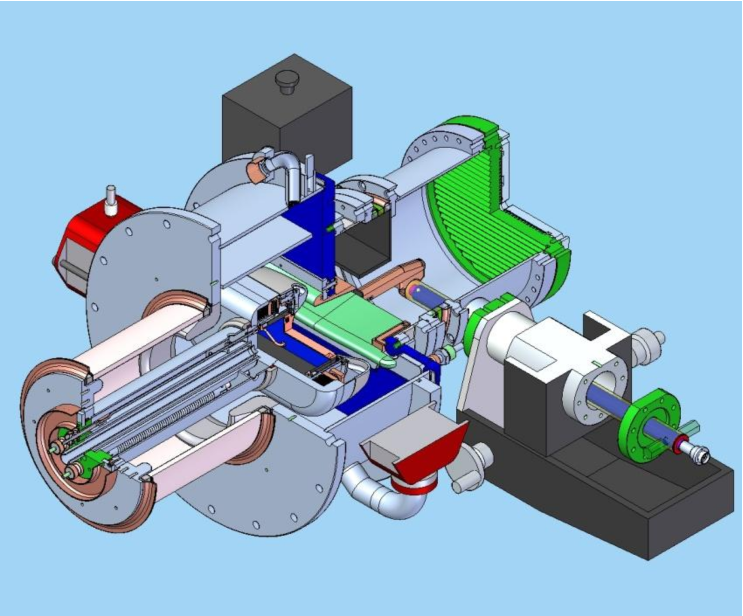
RF Simulations with Magic 2D

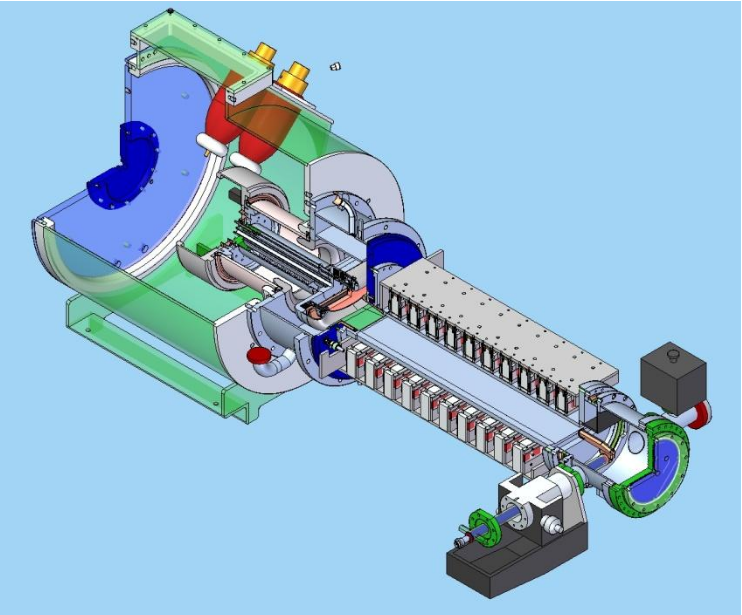
(Assuming Up-Down Symmetry)





Design/Test Evolution



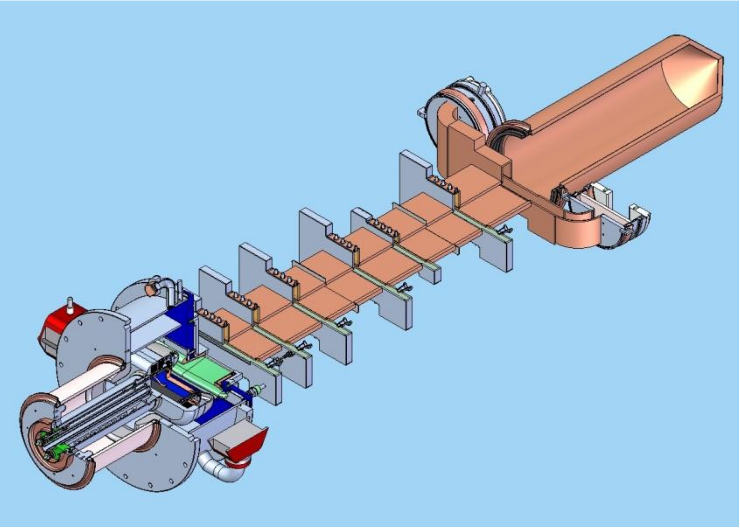


Measure Beam
From Gun

Measure Beam
after Transport
w/o RF

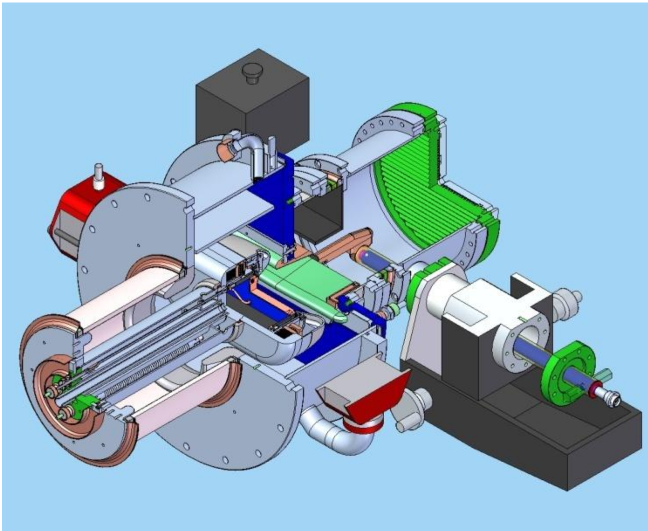
Original Plan

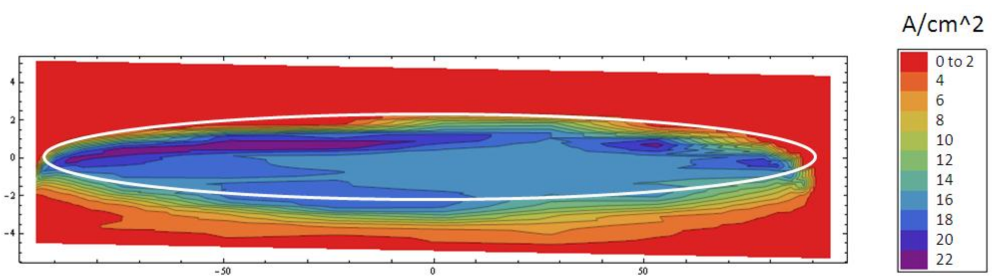
Measure RF
Generation

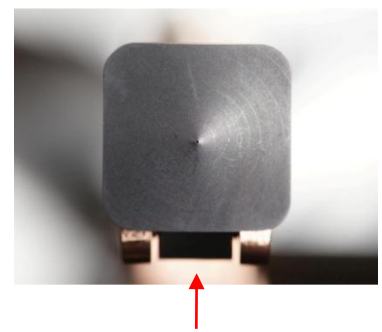


Rotational Alignment of Gun Stem

Beam Tester Results



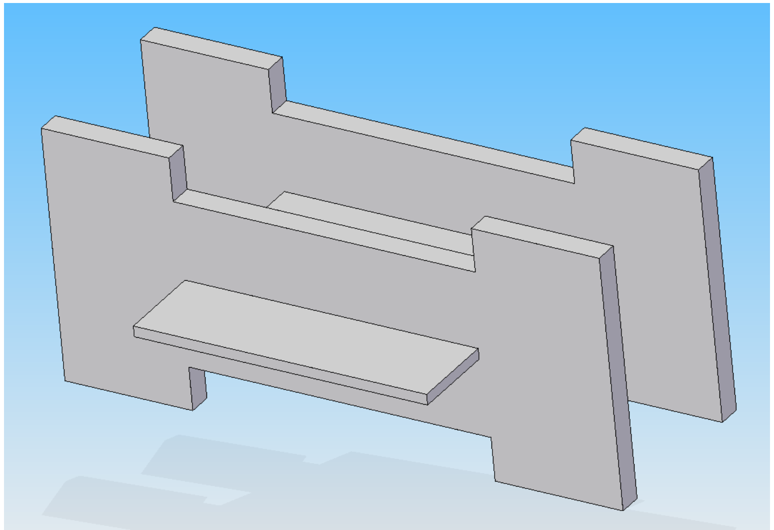




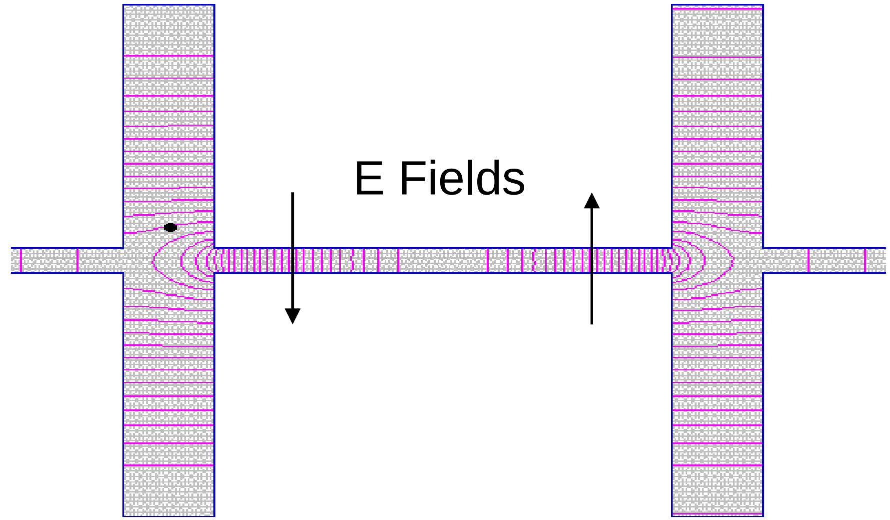
During the tests, had to run a very low pulse rate as ‘sputtered’ carbon from the beam probe shield poisoned the cathode.

A vertical asymmetry was observed in the measured current density profile that was partially corrected using a 900V and 0V bias on the upper and lower focus electrodes, respectively The resulting current density is shown above - an ideal elliptical beam profile outline is superimposed in white.

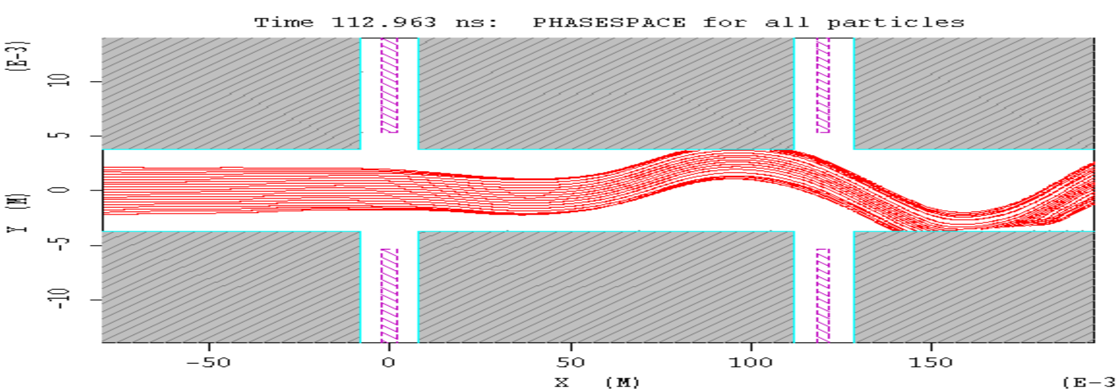
Trapped Modes Between Cavities



Two Cavity Geometry



Two Cavity Trapped Mode



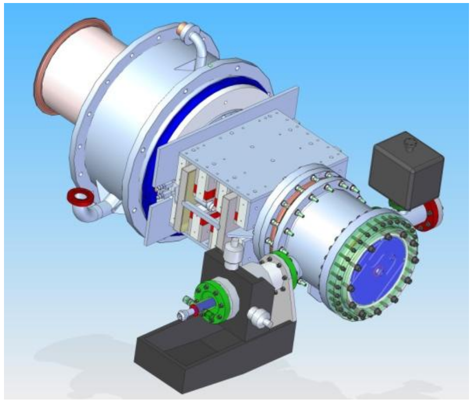
Trapped Mode Interaction with Beam (MAGIC2D)

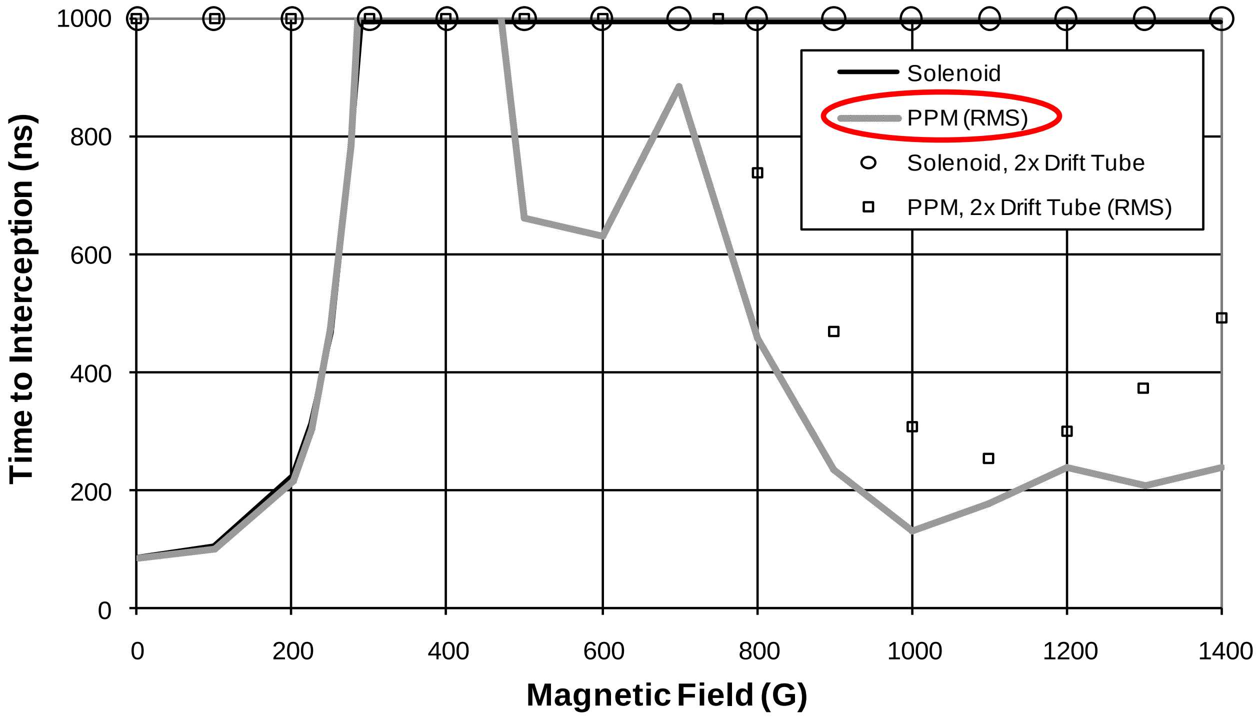
A collaboration of Linear Collider, Beam Physics, Advanced Computations and Klystron Department physicists have been studying this problem for over a year.

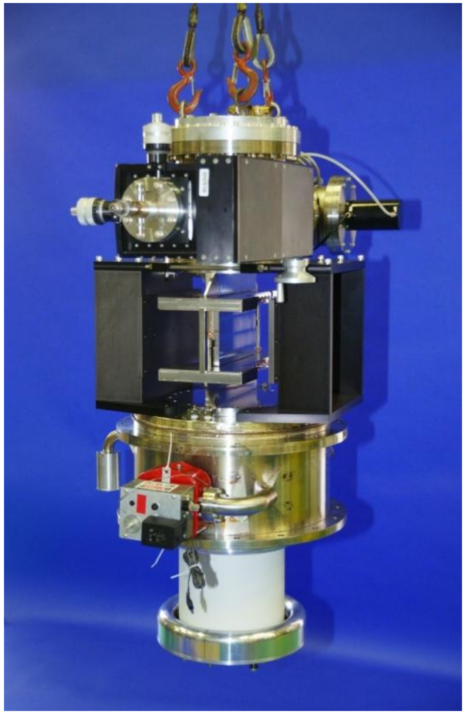
Two-Cavity Stability Test

Found no simple means to suppress the modes in simulation without doubling the drift tube height to decrease cavity coupling and a using solenoidal magnet to increase the focusing strength.

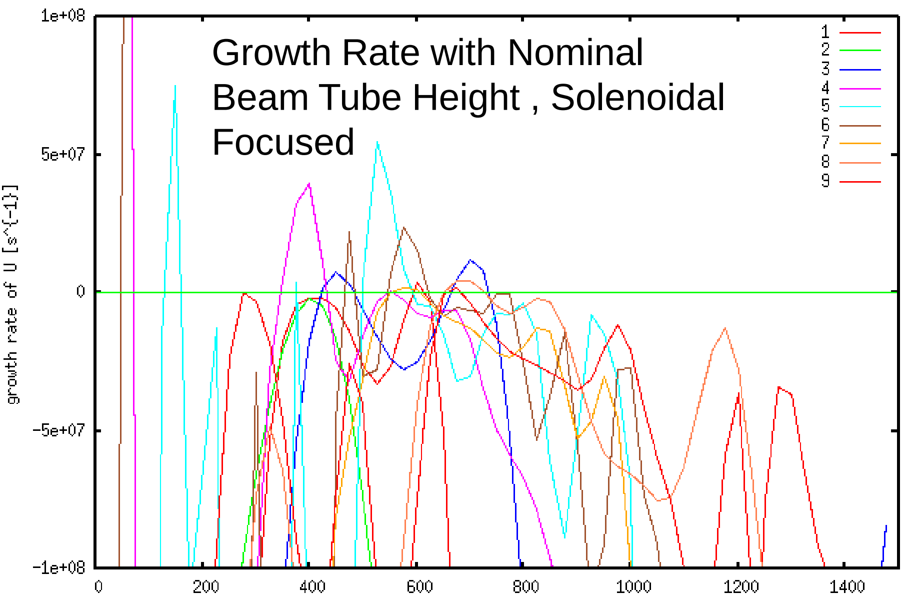
Built a two-cavity oscillation device using the Beam Tester and parts from the original permanent magnet focusing system. It will be operated to verify the predicted regions of stability vs magnetic field

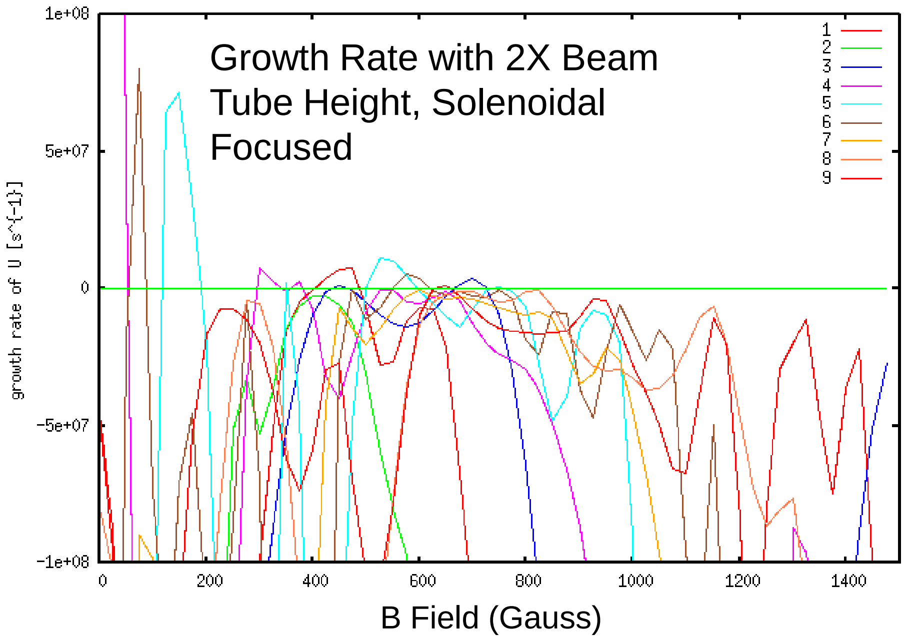


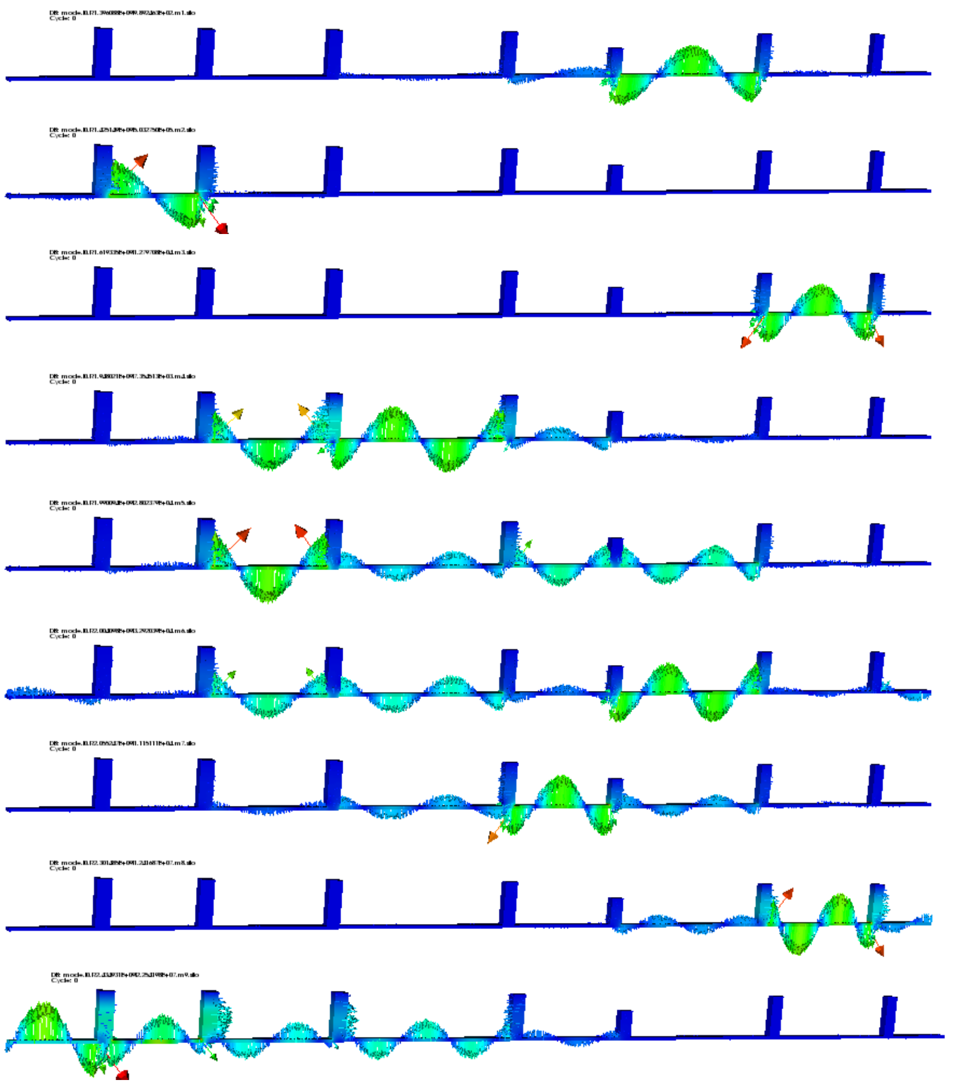




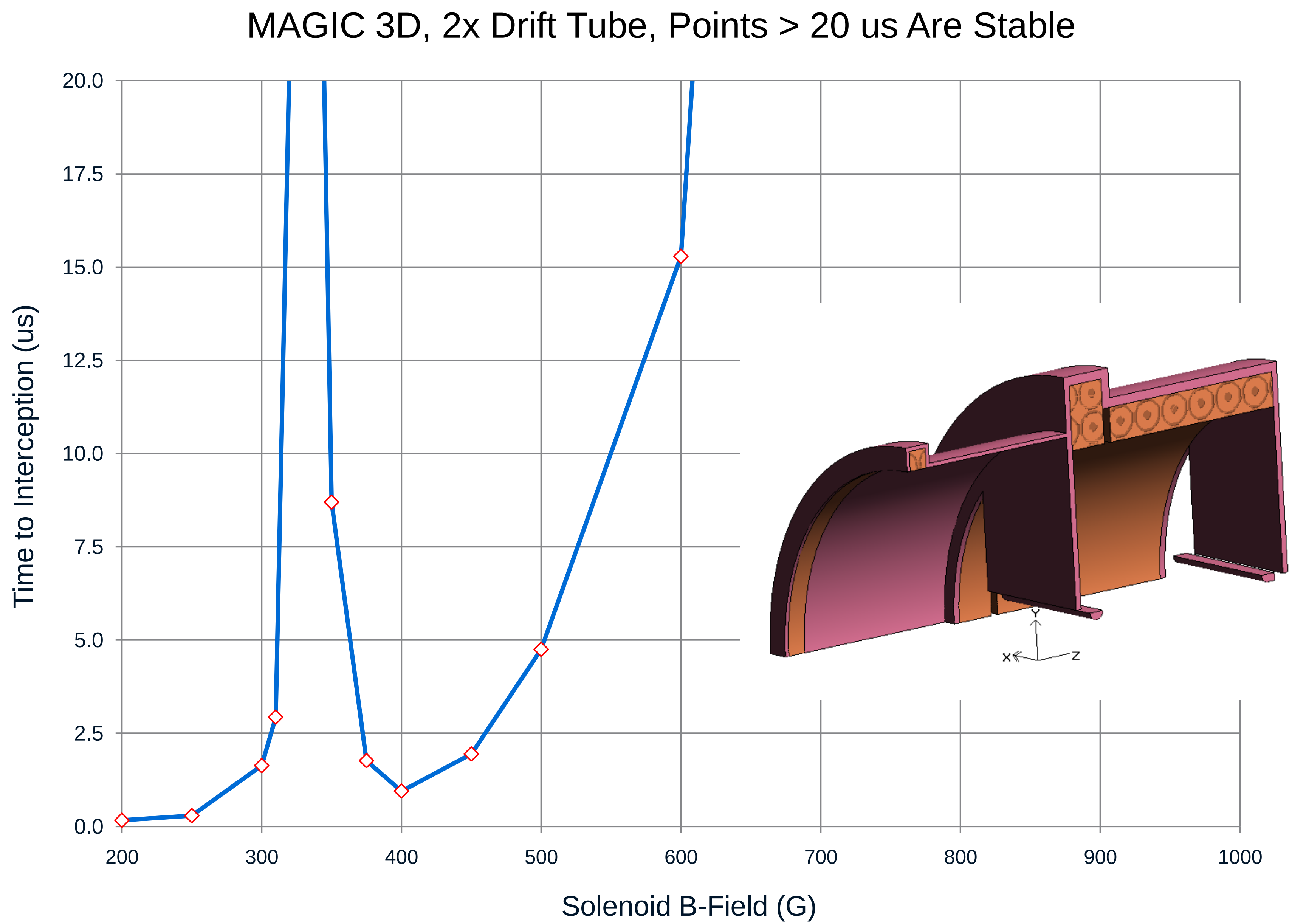
Modes with 7 Cavities: 1.4-2.4 GHz







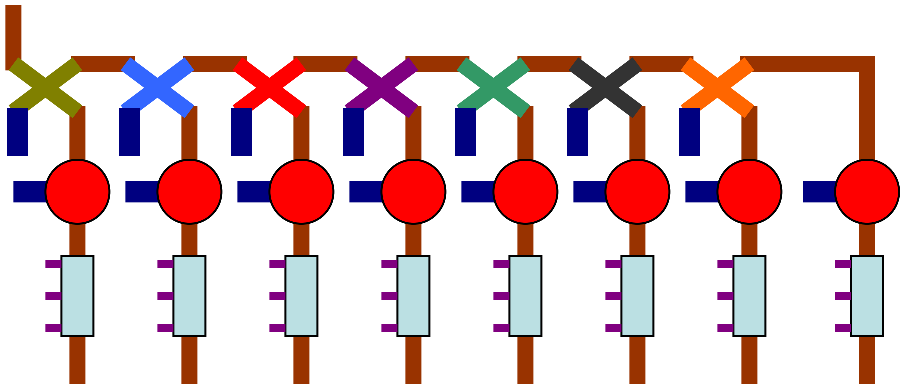
Full SBK (7 Cavity) Stability vs. Solenoid B- Field



Optimized RF Distribution System

- **Goals:**
  - Pursuing two changes to the baseline local distribution scheme to lower its cost: (1) Use hybrids instead of isolators and (2) Variable Tap-Offs (VTOs) instead of fixed tap-offs to accommodate the large spread in cavity gradients
  - Build such systems for FNAL cryomodules (CMs)
  - Develop a Klystron Cluster distribution scheme that would move rf sources to surface buildings, eliminating the need for a service tunnel
- **Project Status:**
  - An 8-cavity distribution system was built and sent to FNAL in FY09 Q2 to power their first CM. A second one is being built that will have remotely controlled VTOs
  - For Klystron Cluster scheme, constructing a 10 m demonstration section that will achieve the same peak surface fields as would be present in the ILC

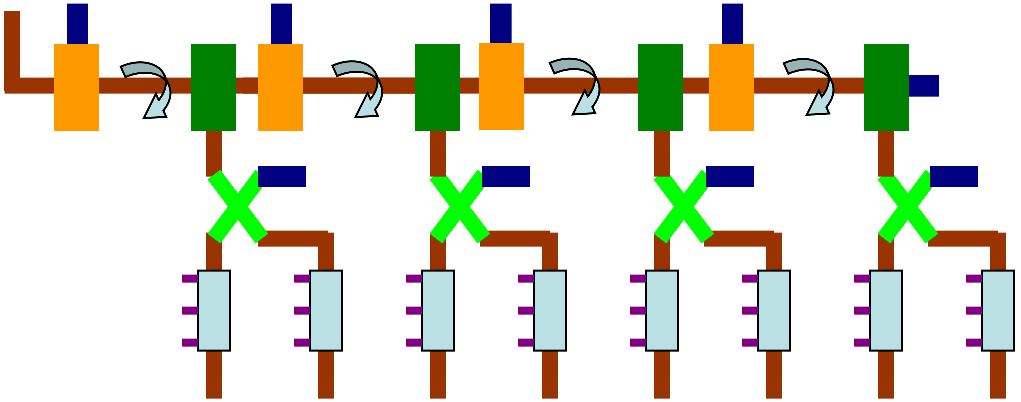
ILC Baseline RF Distribution System



Fixed Tap-offs

Isolators

Alternative RF Distribution System

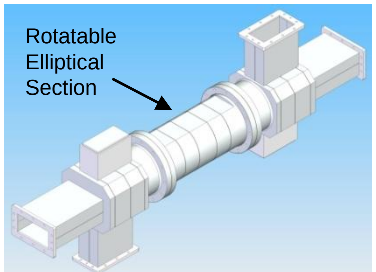


Variable Tap-offs (VTOs)

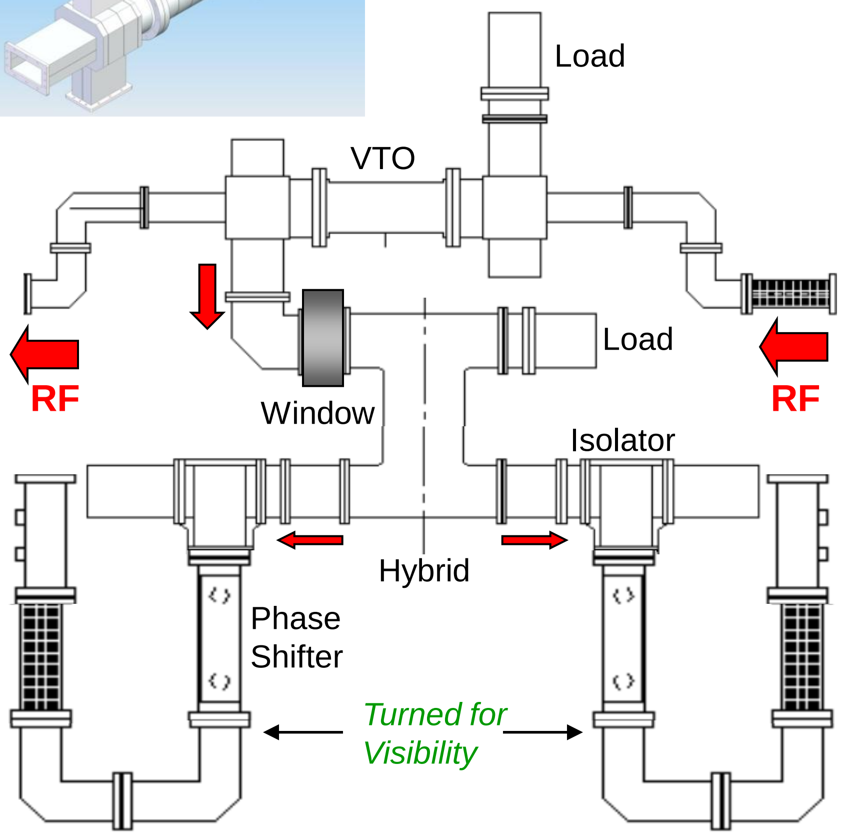
3 dB Hybrids

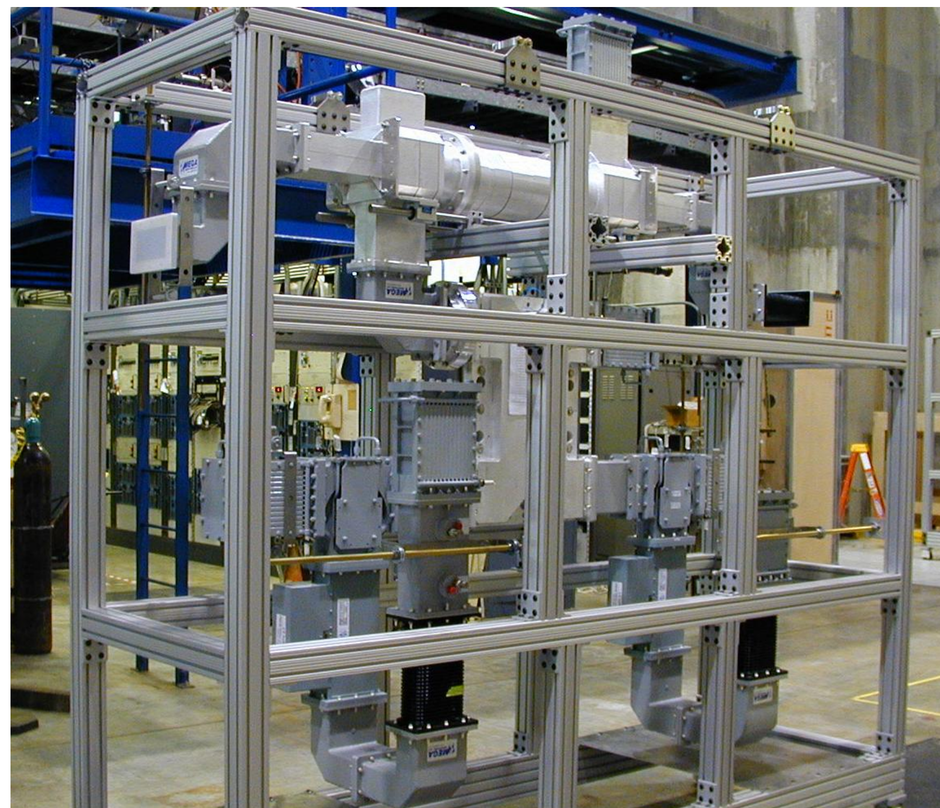
RF Distribution Modules

Four, two-cavity distribution modules were individually high power tested and then shipped to FNAL in FY09

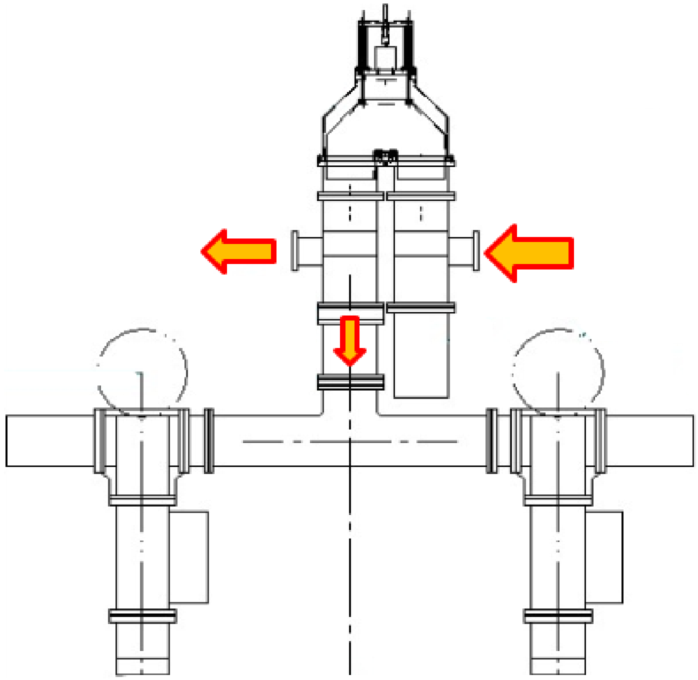


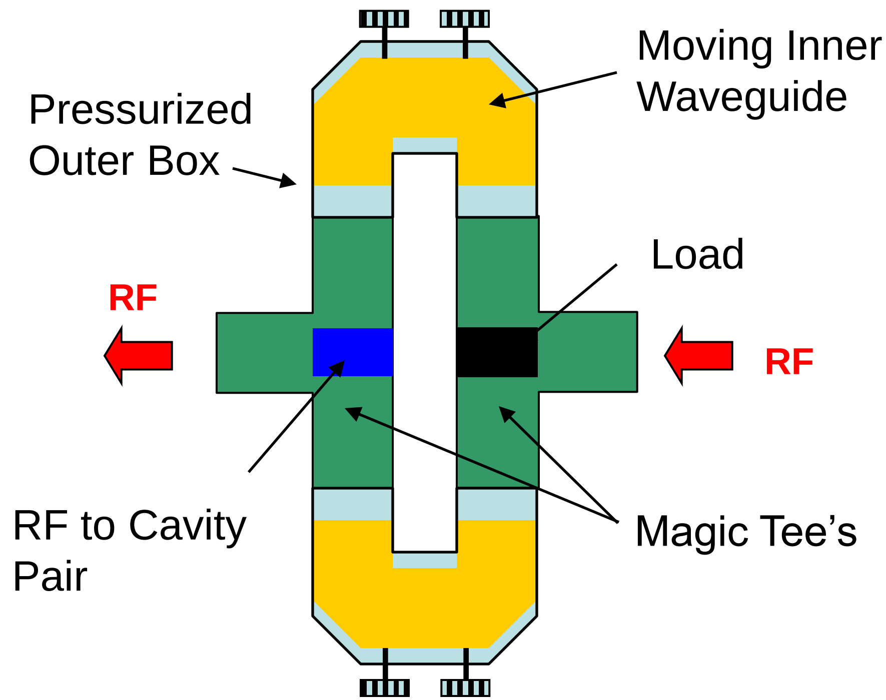
Elliptical Variable Tap-Off (VTO)

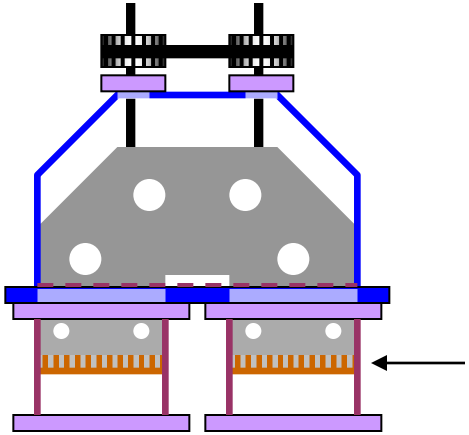




Building Simpler VTO For Next CM







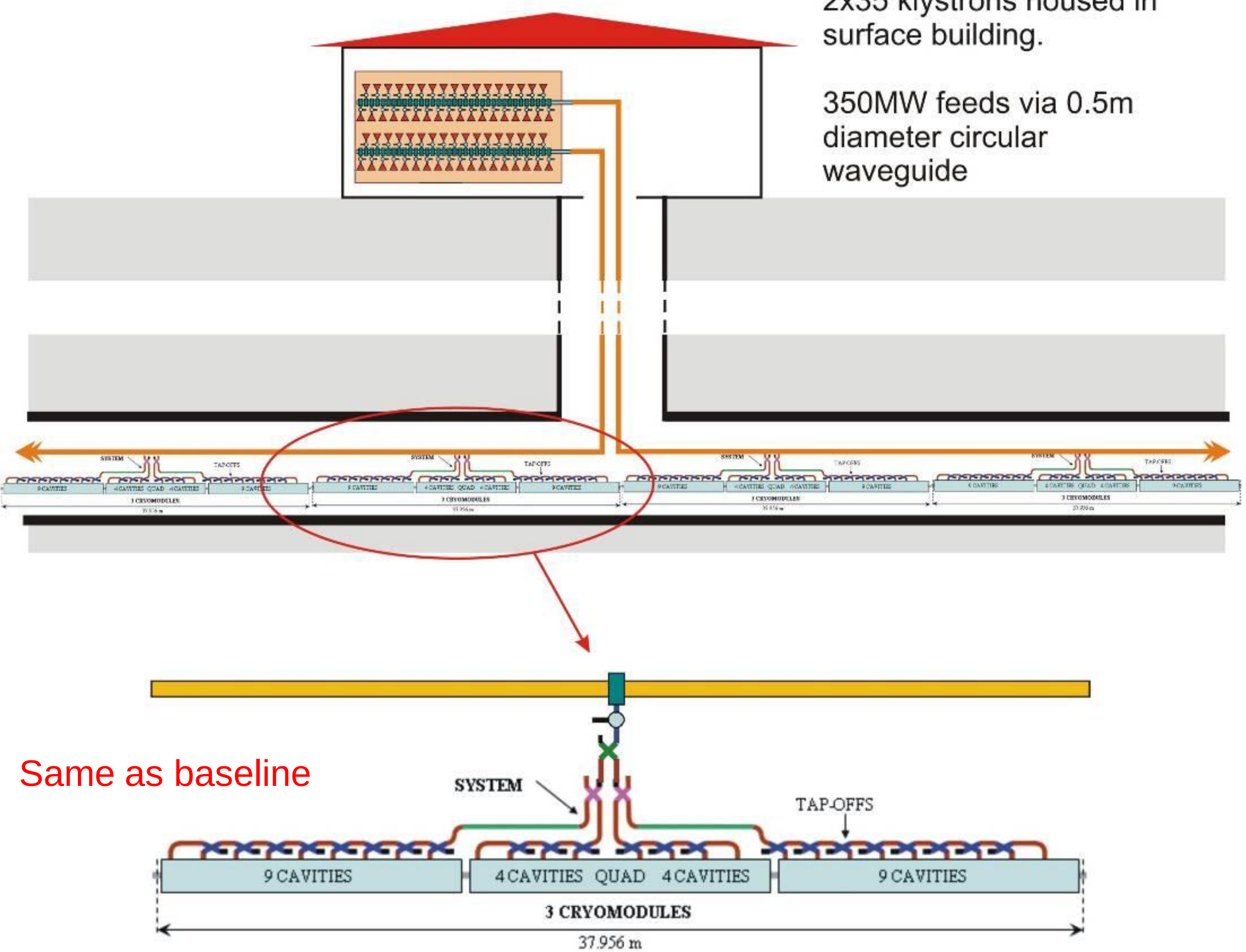
Use commercial 'folded' Magic Tee's

Put remotely controllable phase shifters into U-bends – relative phase controls power split

Match ideally unaffected by position

No bellows but need 'finger' stock to cut off RF

Klystron Cluster Concept



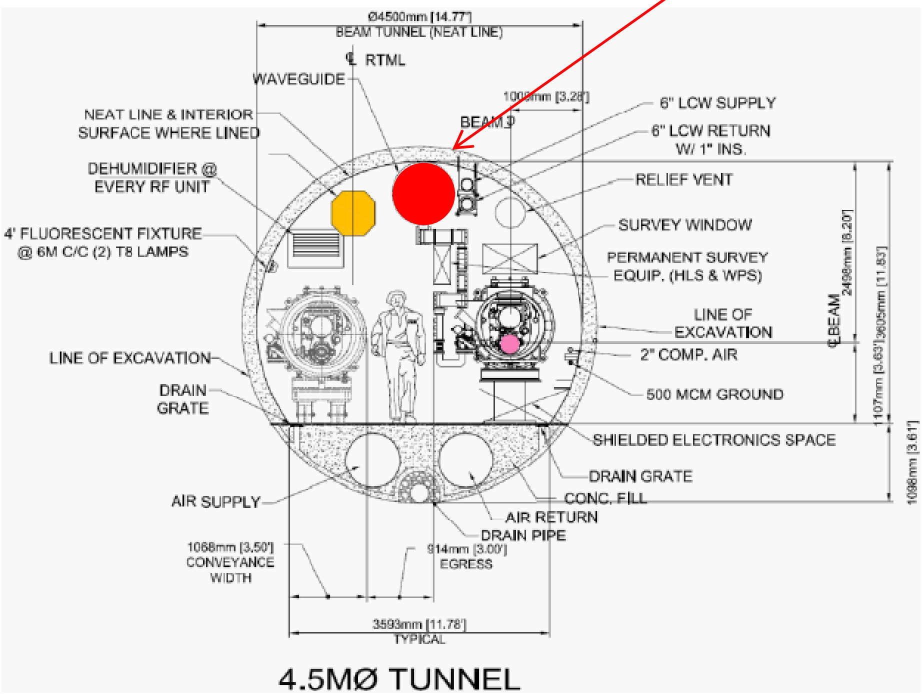
Same as baseline

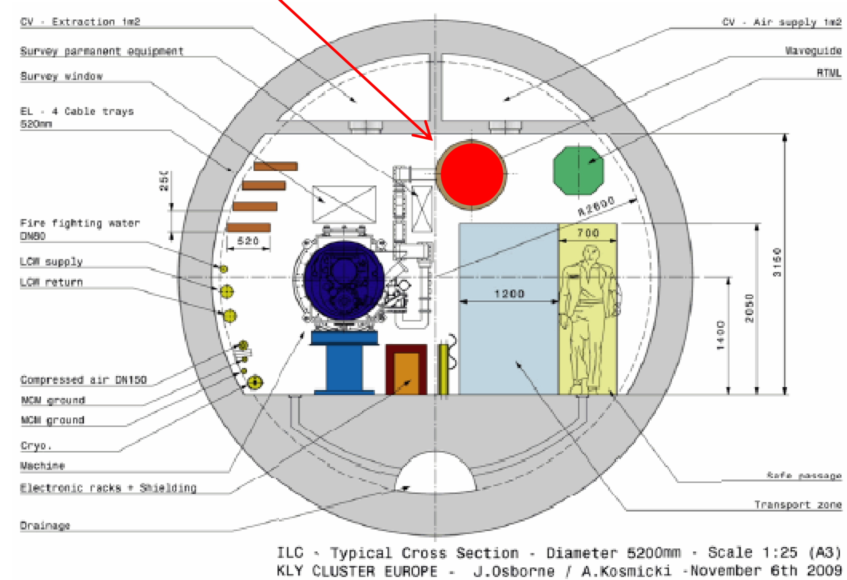
Each tap-off from the main waveguide feeds 10 MW through a high power window and probably a circulator or switch to a local PDS for a 3 cryomodule, 26 cavity RF unit (RDR baseline).

- RF power "piped" into accelerator tunnel every 2.5 km
- Service tunnel eliminated
- Electrical and cooling systems simplified
- Concerns: power handling, LLRF control coarseness

Single Tunnel Layout with KCS

RF Waveguide

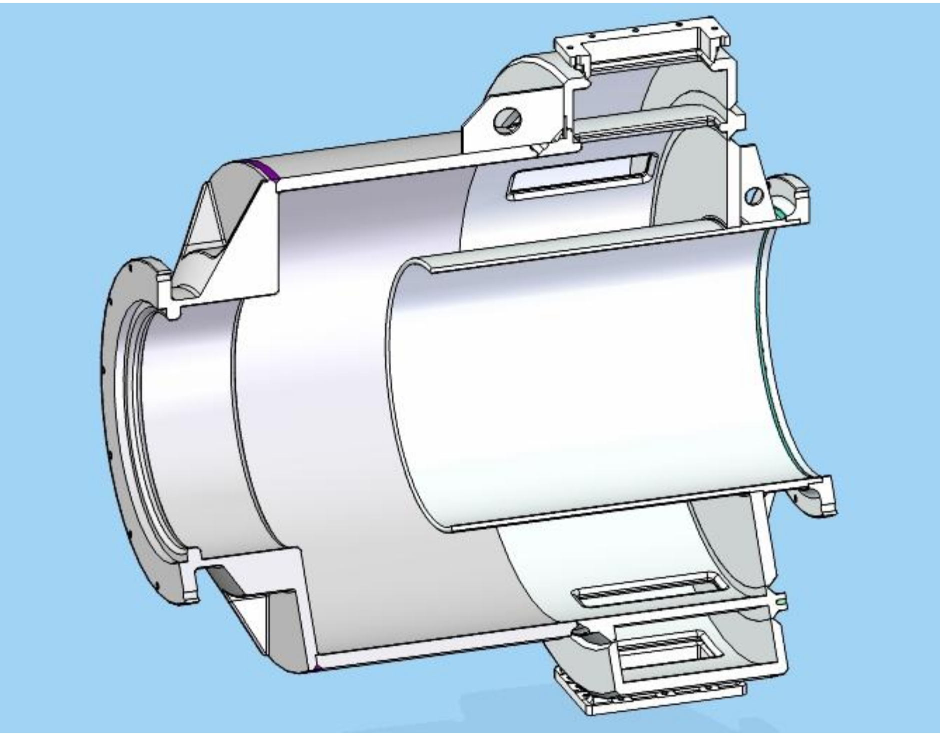


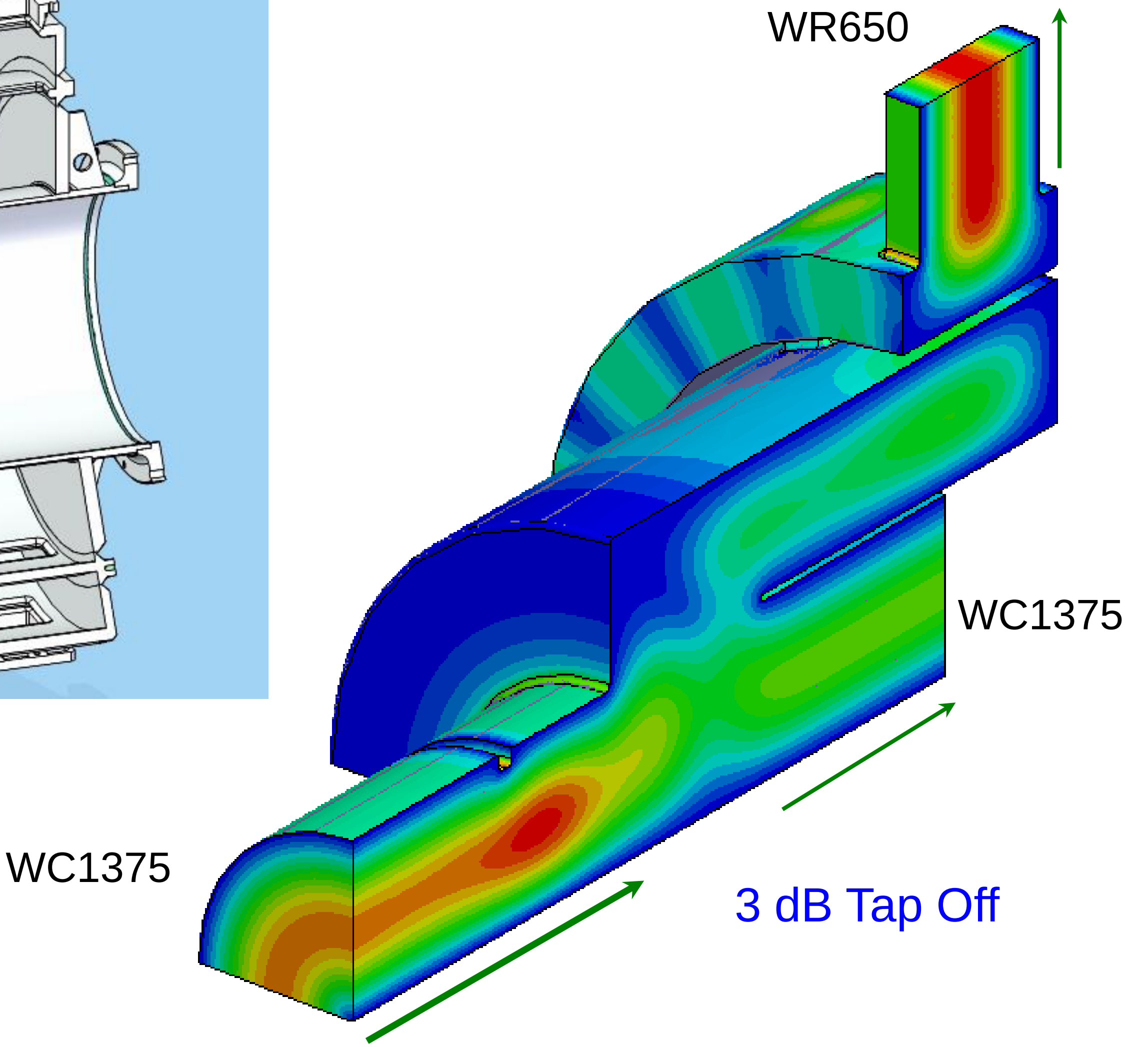


Americas Region

European Region

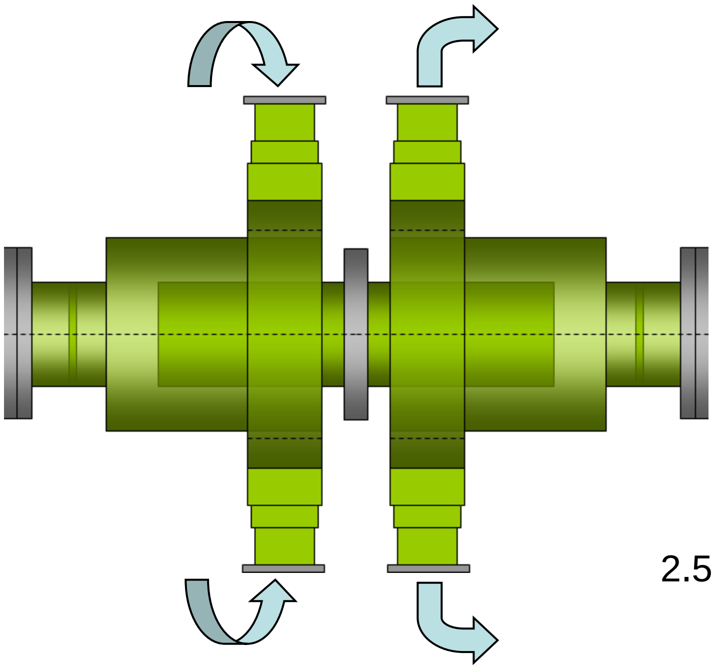
Coaxial Tap Off (CTO)





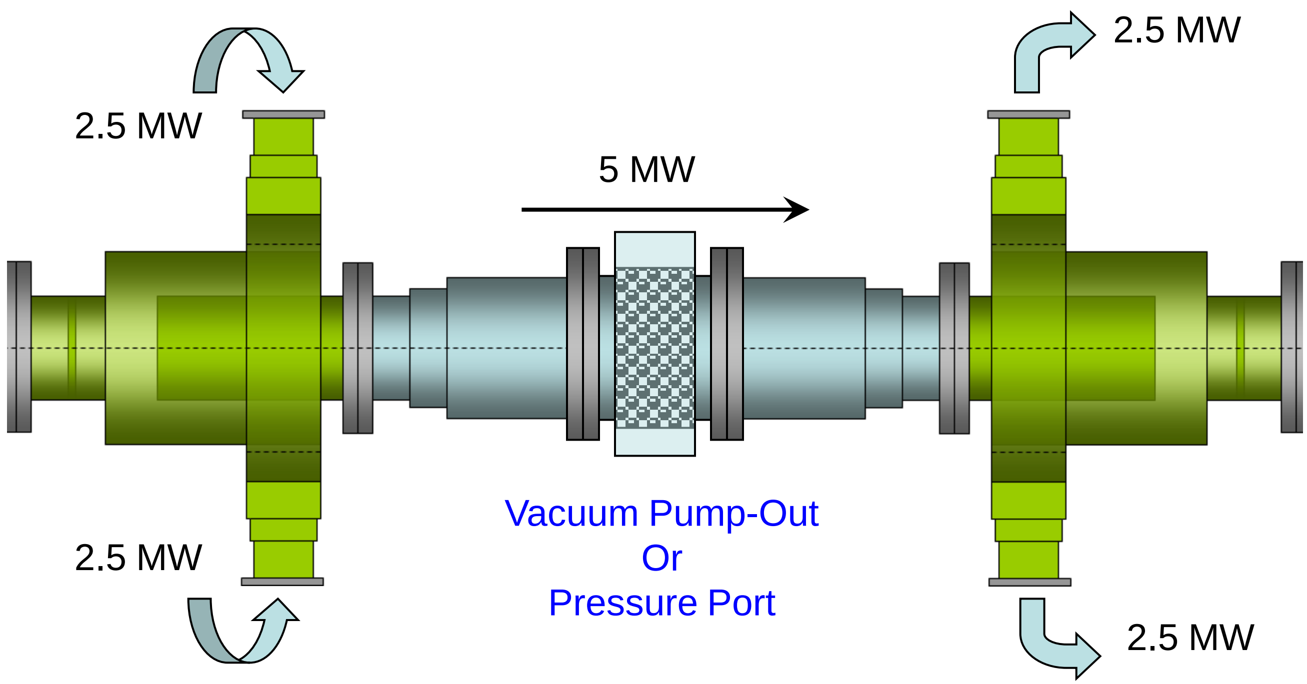
Phase I Demonstration Steps

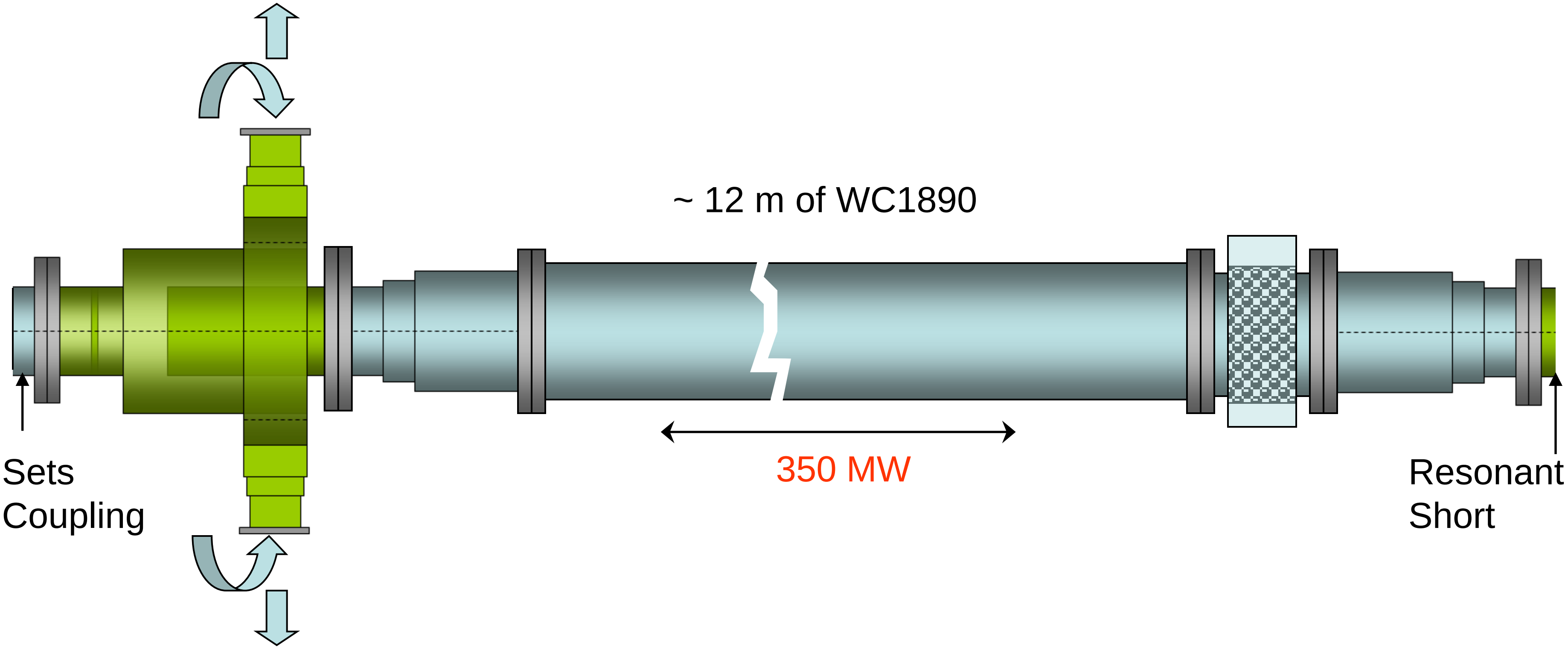
(To Be Completed in Few Months)



Step 1: Build two 3dB CTO’s, short port 1’s to make launcher/extractors, and cold test back-to-back (verify w/ spacer).

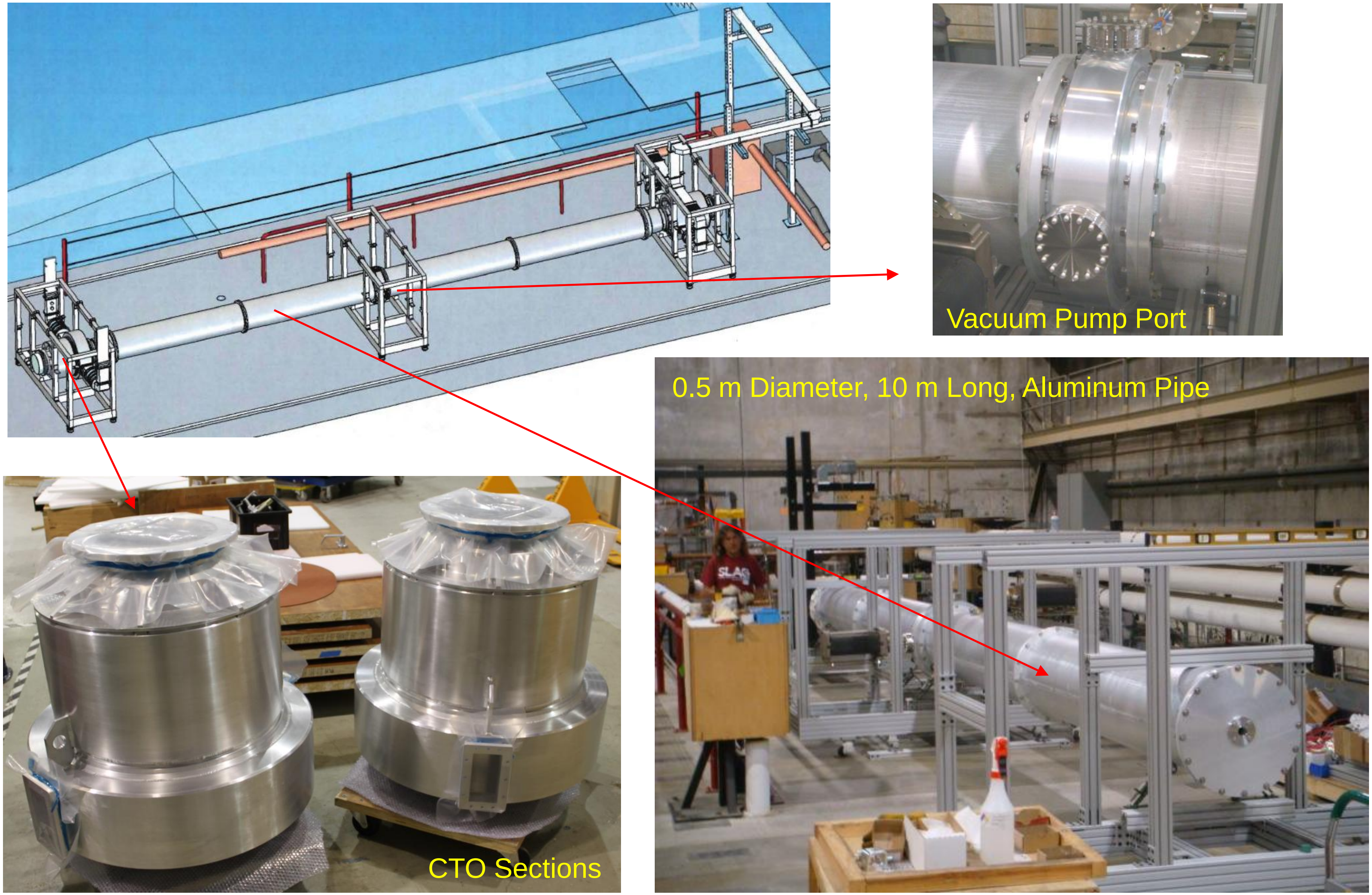
Step 2: Build step tapers and pump out, include in assembly, cold test again, and high power test up to 5 MW.





Step 3: Adjust input coupling (beta = 6) and resonantly charge the line (tau = 8 us) to field levels equal to those for 350 MW transmission (requires only 2.5 MW of klystron power). Do this under pressure (2 bar absolute) and under vacuum (< 1e-6 Torr).

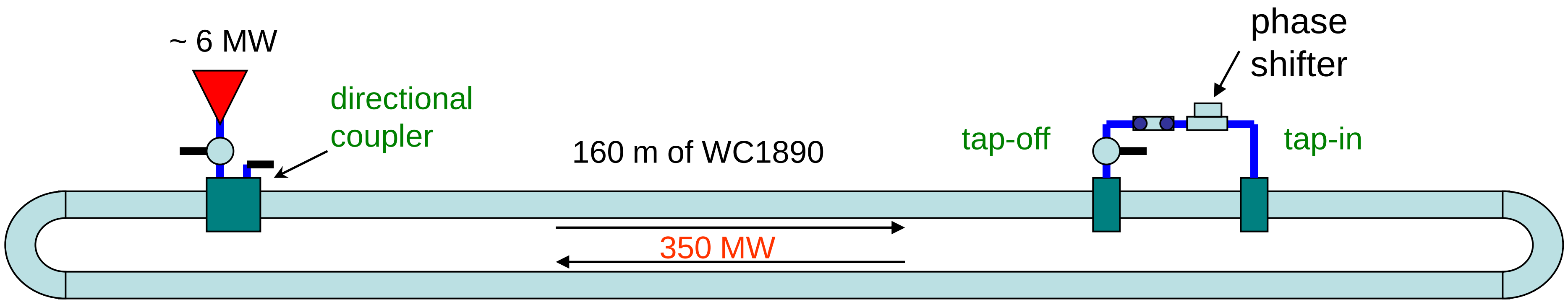
KCS Test Bed at SLAC ESB



Phase II Demonstration

(To Be Completed in 2012)

Develop bends and configure a 160 m resonant ring to test them and a final design tap-in/off. Stored energy is about 1/5 of the worst case in the ILC with speed-of-light limited klystron shutoff time.



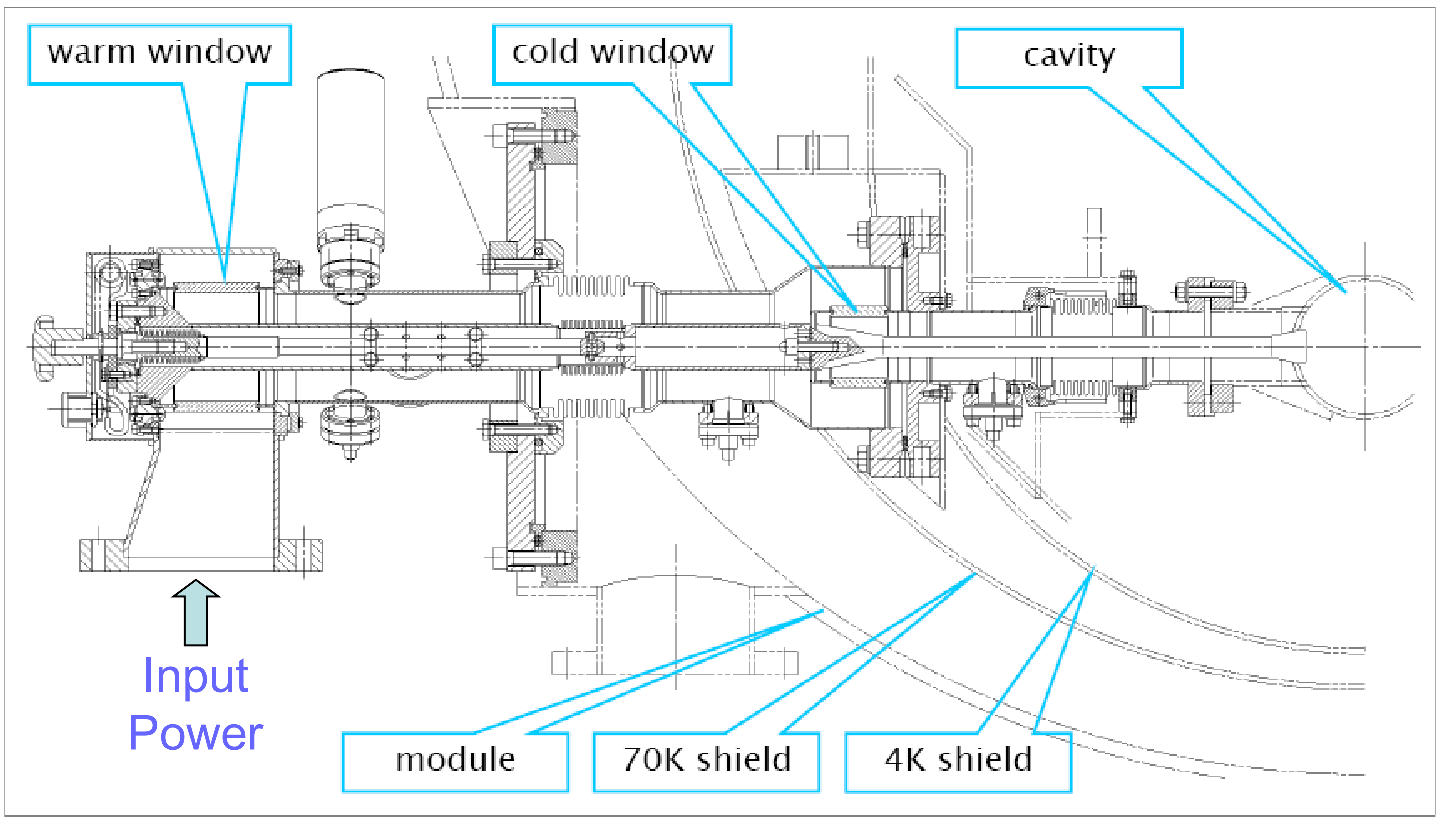
Coupler Assembly & Processing

- **Goals:**
  - Clean and assemble pairs of couplers in SLAC's Class 10 Cleanroom, bake and rf process them at the L-Band test area in End Station B and then ship to FNAL for use in the NML cryomodules
  - Develop less expensive means of fabricating couplers
- **Project Status:**
  - Have processed 10 of the 12 couplers originally purchased by FNAL two years ago
  - In FY10, ordered 10 more from CPI with ILC funds, and 22 more with ARRA funds – new couplers should start arriving this month
  - Working closely with FNAL to ensure couplers can be easily installed on the cavities
  - Building a cold section using induction brazing and TIG welding instead of e-beam welding so more vendors can build them

TTF-3 Coupler Design

Design complicated by need for tunablity (Qext), dual vacuum windows and bellows for thermal expansion.

Coaxial Power Coupler

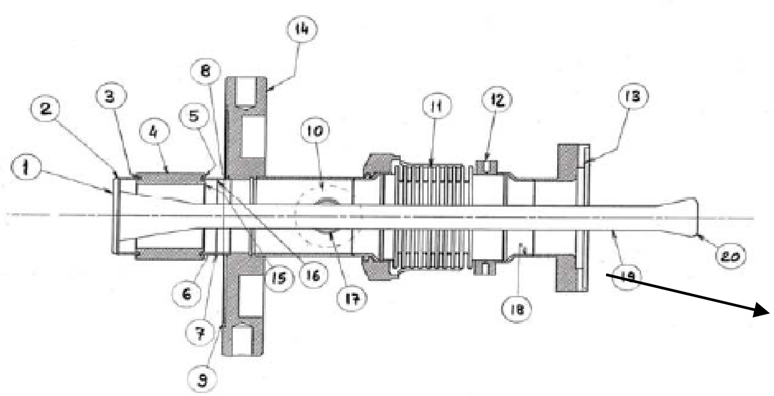


Coupler Inspection

STANFORD LINEAR ACCELERATOR CENTER

TTF3 Coupler Metrology Report

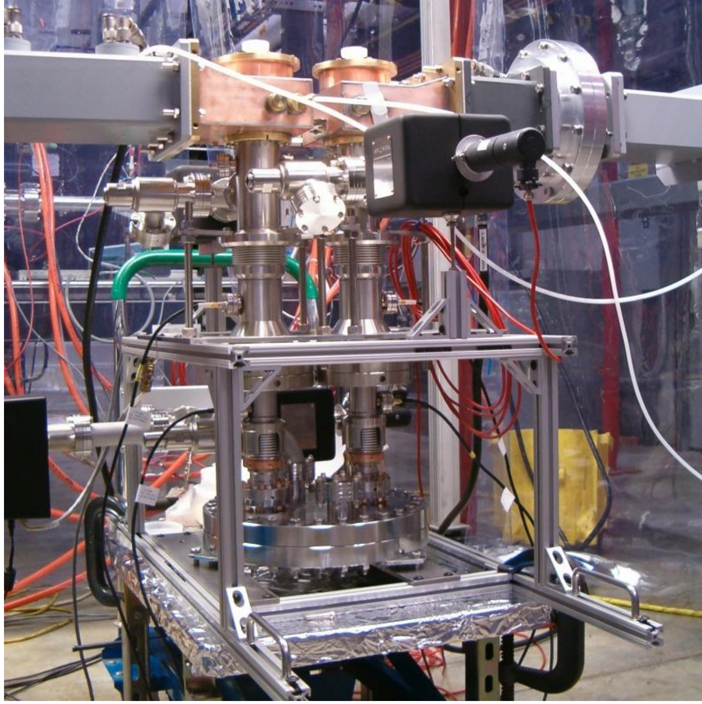
Inspection of Cold Part 3964328/A.000					
Serial Number:	CP3C41	Inspector:	Keith Caban (CMM)	Date:	11/9/2007
Serial Number:	CP3C41	Inspector:	Tom Nakashima Video	Date:	11/14/2007



Item	Inspection Criteria	DESY Print Number	LAL Print Number	Findings	Pass
1	Visual: Nicks, scratches, proper edge chamfers	3964328/A.003	I65-3D-1250		X
2	Visual: Weld form, size, and porosity	3964328/A.000	I65-2E-1200		X
3	Visual: Brazing: Irregularities, centering of groove , buildup Ceramic: metallization borderline,coverage, chamfer	3964328/A.200	I65-3S-1260		X

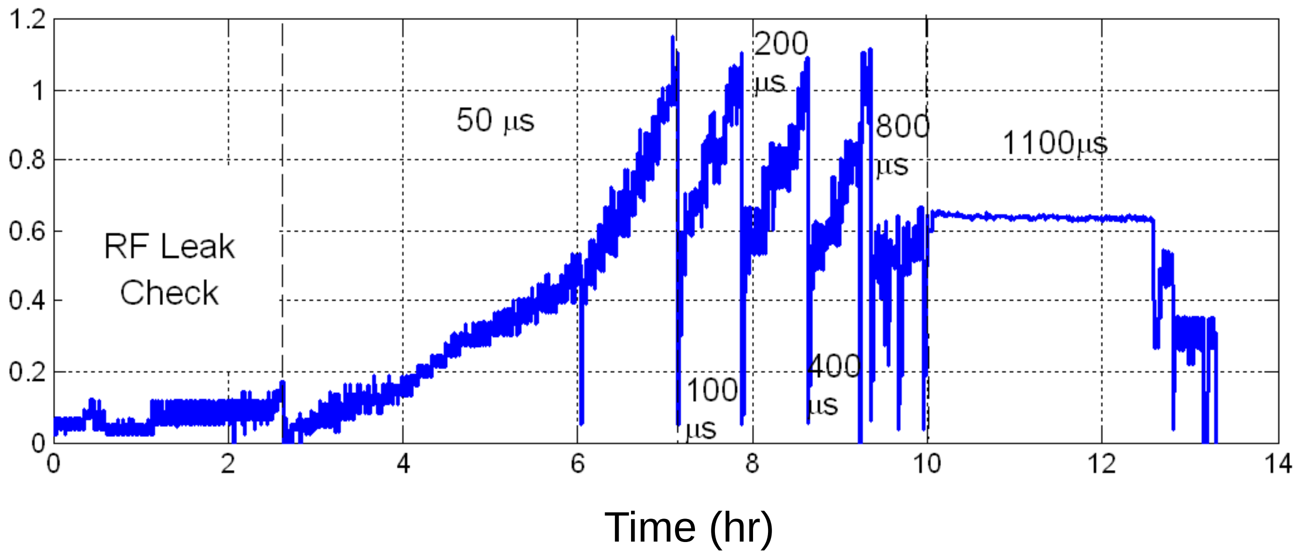
Coupler Assembly in the SLAC Class 10 Cleanroom

RF Processing of Coupler Pairs



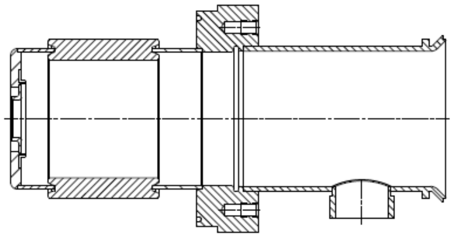
Processing of first pair sent to FNAL: Power (MW) -vs- Time for Pulse Widths of 50,100, 200, 400, 800, 1100 μs

Processed Fast by Historical Standards

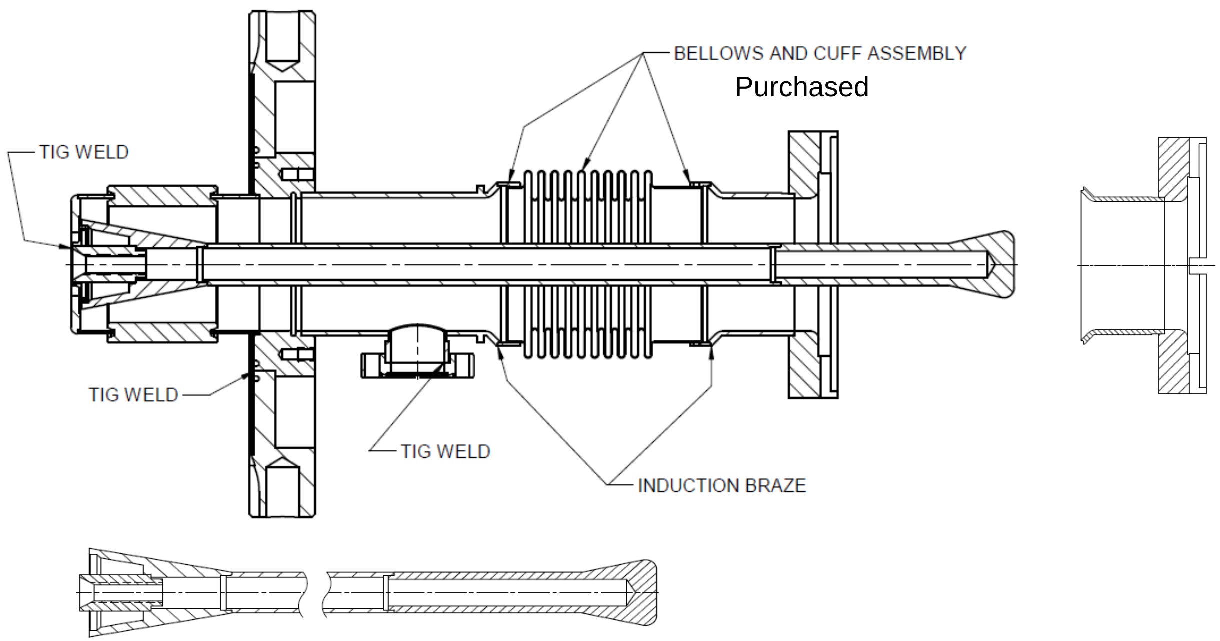


Fabrication Simplification

Currently building a ‘cold’ coupler section using TIG welding and induction brazing of parts assembled using conventional brazing techniques (Cu plate parts first, then braze and TiN coat window before final assembly). The antenna is hollow and vents to the warm section.



Conventional brazements and final assembly



FY11 ILC RF System / MLI Program

- Continue operation of the P1 Marx (driving the Toshiba MBK), complete the P2 Marx and acquire the DTI Marx if factory tests are successful
- Evaluate performance of existing MBKs (SLAC/DESY) and test a second unit from industry (the Toshiba MBK will eventually go to FNAL)
- ARRA/ILC: Complete the second rf distribution system for FNAL CM2 (with remote power/phase control) and start a third for CM3 (Type 4).
- Klystron Cluster scheme for ILC – if 350 MW tests of the current 10 m section are successful, extend length to 80 m and produce a prototype bend.
- ARRA: Continue coupler production for FNAL and the program to industrialize the TTF3 couplers (have industry build several cold sections based on the SLAC fabrication development)
- Other: Complete beam HOM heating studies, continue evaluation of the impact of KCS on beam emittance in the linacs, and participate in the cavity gradient stability studies at FLASH.

Summary

- Marx/MBK undergoing long term testing, the P2 Marx design is well along and are in the process of acquiring a Marx built by DTI through SBIR funds
- SBK program coming to an end – learned a lot that can hopefully be applied to other applications. Will purchase a second MBK to help qualify more vendors.
- Local rf distribution and coupler program making good progress
- Klystron Cluster tests will ramp up in scale if initial results promising – ‘big bang for the buck’ in the effort to lower the ILC cost